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GEORGIA INSTITUTE OF TECHNOLOGY
Engineering Experiment Station
Atlanta, Georgia

FINAL REPORT

PROJECT A-1026

# INVESTIGATION OF THE ATMOSPHERIC ABSORPTION INFLUENCING FAR INFRARED LASER SIGNAL TRANSMISSION

By

K. H. Breeden, A. McSweeney
and A. P. Sheppard

15 February 1970



CONTRACT DAAD07-67-C-0339

**ATMOSPHERIC SCIENCES LABORATORY**
WHITE SANDS MISSILE RANGE, NEW MEXICO

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## ABSTRACT

Measurements on the absorption due to rotational transitions of atmospheric water vapor in the 10 $cm^{-1}$ - 100 $cm^{-1}$ frequency region are reported. Comparison of the measured absorption line center frequencies is made with the theoretical calculations of other investigators. Measured absorption in the atmospheric "windows" is also compared with theoretical predictions. Good agreement is obtained between theory and measurements. A summary of instrumentation used and techniques for processing the data is given. The instrumentation centers about a 30 cm aperture Michelson interference spectrometer and an auxiliary multiple reflection chamber in which a test atmosphere can be monitored and controlled. A discussion of humidity measurement techniques is also presented.

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INVESTIGATION OF THE ATMOSPHERIC ABSORPTION INFLUENCING FAR INFRARED SIGNAL TRANSMISSION

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## I. Introduction

The extension of laser techniques to the far infrared by Gebbie et al., in 1964[1] opened some new avenues for applications of this portion of the electromagnetic spectrum. For the first time a coherent source was available which did not have the built-in weaknesses so inherent to microwave tubes as their frequency of oscillation is extended upward. Since 1964 many other laser transitions have been observed and good coverage of the 100 - 1000 μm wavelength region is possible.

Concurrent with the laser frequency extension to the far infrared, liquid helium cooled germanium bolometers were improved so that Low[2] has reported on a unit with sensitivity of $10^{-14}$ watts/Hz$^{\frac{1}{2}}$. The laser also opens possibilities for superheterodyne detection should applications demand or warrant greater available sensitivity in receivers for the far infrared.

The high resolution and wide modulation bandwidths may, of course, be cited as potential advantages for any frequency region, including the far infrared, that is above the presently widely used microwave spectrum. Likewise, components tend to get smaller in volume and lighter in weight as frequency increases. The primary distinguishing factor associated with the far infrared is that rotational transitions of water vapor cause substantial atmospheric absorption of electromagnetic energy propagated in the 100 - 1000 μm region. The magnitude of this absorption practically precludes any long range communications or radar system. However, for short range, very secure communications using the 100 - 1000 μm region would be ideal. One of the most interesting possibilities of immediate interest for the 100 - 1000 μm region would be using it for remote sensing of atmospheric gases.

Prior to undertaking any systems calculations or projections for the far infrared, it is imperative that more accurate data be obtained on the center frequencies of the water vapor absorption lines and on the magnitude of the absorption coefficient as a function of frequency, particularly in the "windows." It has been the purpose of this research to obtain such data. This report serves to compile and document these data and to summarize information on the equipment and techniques used to obtain the data.

## II. Background on Atmospheric Absorption due to Rotational Transitions of Water Vapor

Water vapor has a large molecular electric dipole moment and is spectroscopically classified as an asymmetric rotor. This gives rise to a large number of transitions which extend from 1.35 cm to well beyond 100 μm.

A number of theoretical predictions have been made on the atmospheric absorption of water vapor. Van Vleck quantitatively related the shape of the water vapor absorption lines to temperature, pressure, a spectroscopic line width constant, humidity, the effective dipole moment of the molecule, and the line center frequency.[3,4] Many others have since improved and modified Van Vleck's work by considering, for example, such things as the interaction of the water vapor molecules with other molecules, a more rigorous view of the shape factor, and the extension of the number of molecular quantum transitions that must be summed to obtain an accurate prediction of absorption in the "windows."[5-12] Many of these calculations were based on earlier theoretical analysis of the shape of microwave absorption lines[13-15] and the energy levels associated with the water vapor asymmetric rotor.[16-19]

Because of the earlier mentioned lack of sources and detectors in the far infrared, much of the data obtained to date has been primarily of a qualitative nature and spectroscopic resolution has been low. Among those who have reported on far infrared water vapor absorption measurements are: Ginsburg[20]; Vanasse, Strong, and Lowenstein[21]; Yaroslavsky and Stanevich[22]; Farmer and Key[23]; Palmer[24,25]; and, Zhevakin and Naumov[12,13]. Several of these experiments utilized the sun as a source and observed absorption through the atmosphere as a function of zenith angle whereas others utilized a laboratory spectrometer simulating a point to point transmission through constant atmospheric conditions.

As will be seen in the succeeding parts of this report, the measurements performed on this contract were of the laboratory type with selected constant atmospheric conditions.

## III. Instrumentation

A Michelson interference spectrometer was the central piece of equipment used for the measurements reported herein. This spectrometer has been described in detail elsewhere[26], so only its principal characteristics will be reviewed. The spectrometer was constructed at Georgia Tech and has aperture optics 30 cm in diameter and an effective path of two meters. A series of thin Mylar beamsplitters is used throughout the useful wavelength region of the spectrometer which extends from 8 mm to 80 μm. Resolution of the instrument ranges from approximately 0.1 $cm^{-1}$ at 8 mm to 0.2 $cm^{-1}$ at 80 μm. The frequency region of application for the data reported herein ranges from 15 $cm^{-1}$ to 100 $cm^{-1}$ with resolution of 0.3 $cm^{-1}$.

Both a 1000°K crucible oven and a modified commercial mercury arc lamp have been used as black-body sources. For the first twenty months of the contract a Golay cell detector and a 4°K liquid helium cooled germanium bolometer were used in the measurements. For the remainder of the program, an improved liquid helium germanium bolometer was used. This detector can be pumped to 2°K with a hold time of about twelve hours; thus it offers increased sensitivity throughout the infrared.

In making accurate measurements on the magnitude of absorption in the far infrared "windows," it is necessary to have some auxiliary test chamber between the black-body source and the spectrometer itself. By using the auxiliary chamber, the spectrometer itself is always operated in vacuo so that negligible changes are introduced on the drive screw and optics due to changes in pressure, temperature and humidity. Also, the auxiliary chamber permits a longer path for obtaining data on weak absorption lines. The auxiliary chamber was designed so that a variable length path which would extend from two to forty meters could be chosen by using a multiple reflection geometry.

An interferogram is taken first with the auxiliary chamber evacuated, and then one is taken with the desired atmospheric pressure and humidity in the auxiliary chamber. After power spectra of these interferograms are calculated, their ratios can be obtained for each frequency of interest, and a measure of absorption is obtained for whatever path length is used in the auxiliary chamber. The details of these calculations will be examined in greater detail in Section IV.

Figure 1 illustrates the auxiliary multiple reflection absorption cell that was constructed. The mercury arc or crucible oven source used with the spectrometer is placed at A in Figure 1 and focused by mirrors M1, M2, M3, and M4 through a vacuum window C into the multiple reflection path between mirrors M5, M6, and M7, which are separated by their radii of curvature, 81 cm. The beam is finally brought out through another vacuum window from M7 and focused by mirrors M8, M9, M10, and M11 at the 30 Hz chopper disk denoted as E. Figure 2 shows the present arrangement of the spectrometer from which it can be seen that the auxiliary chamber is effectively interjected at mirror M1 with the source becoming external to the chamber. As noted, pressure and humidity in the auxiliary tank are

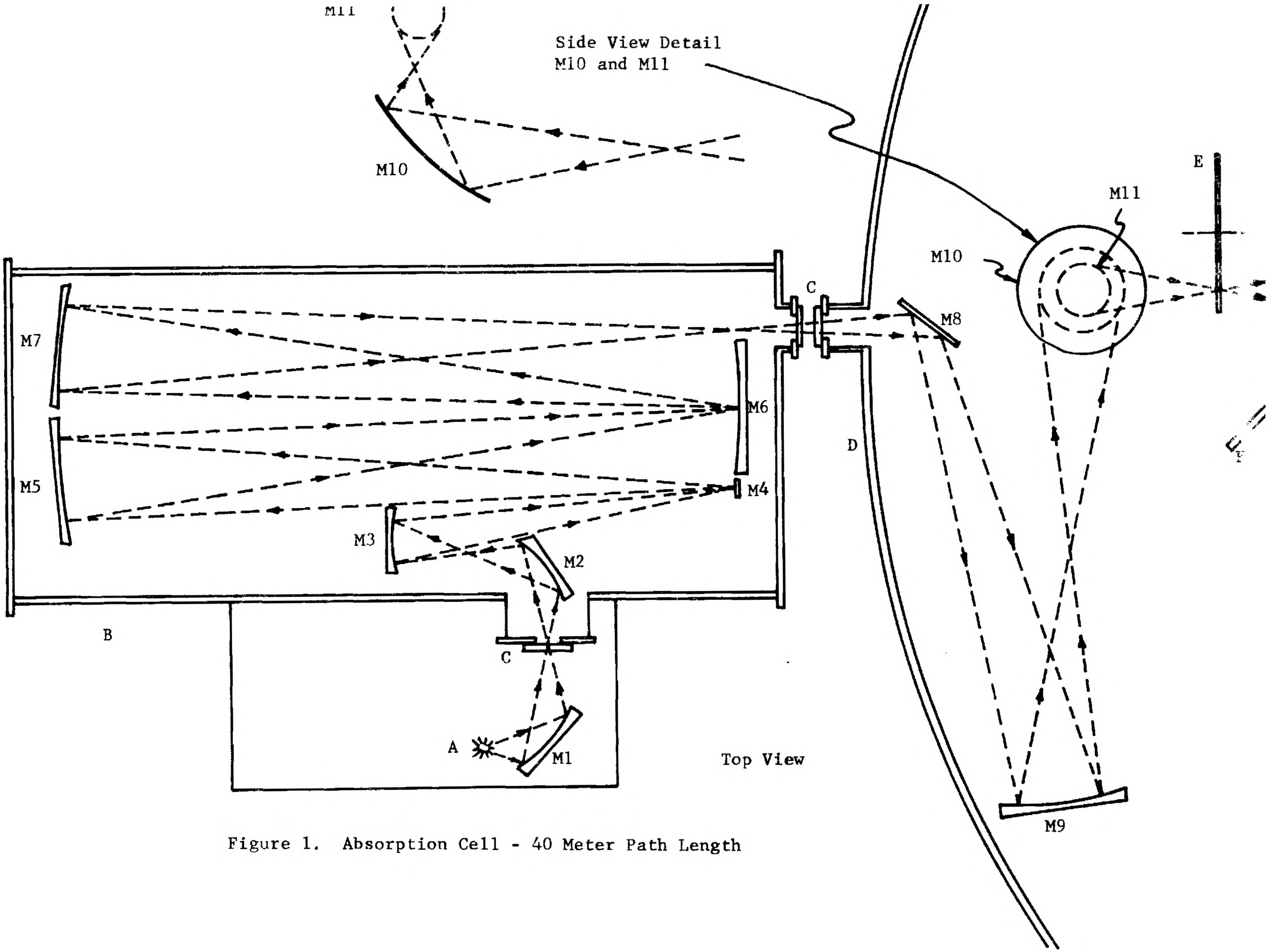


Figure 1. Absorption Cell - 40 Meter Path Length

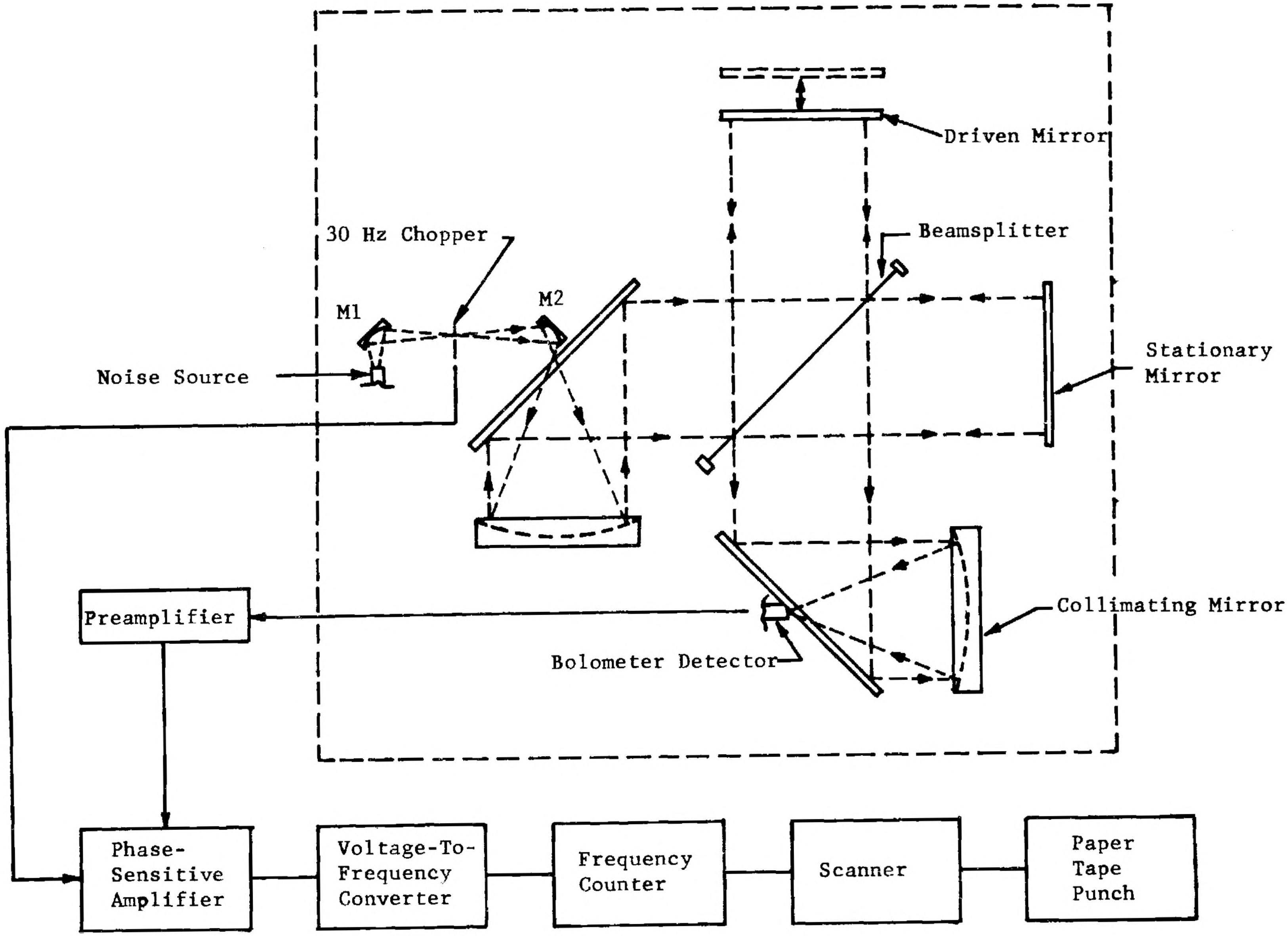


Figure 2. Present Arrangement of Interference Spectrometer

completely independent of the main spectrometer tank. The auxiliary tank is designed to operate at vacuums equal to the limiting forepump pressure, which in this case is about 0.01 Torr, and it contains a metered inlet valve for control of water vapor content and air pressure within the chamber.

Figure 3 is a photograph of the auxiliary chamber as attached to the main spectrometer chamber with a view from the source optics side. Note in this picture that the water-cooled mercury arc is mounted in the source position. Total chamber loss from the source to the main spectrometer collimating optics in vacuo is approximately 5 dB in the 15 $cm^{-1}$ to 45 $cm^{-1}$ frequency band, for a total path of 236 cm.

To obtain quantitative data on water vapor absorption requires accurate measurement of the absorption chamber humidity. A number of techniques were investigated for accomplishing this. A thermoelectric cooler installed directly in the chamber was first used to measure dew point. Primary difficulties with this unit were measurement repeatability and placement of the thermoelectric cooler in a location which accurately represented the absorption path humidity.

Prior to initiation of this research program, a mass spectrometer technique had been eliminated as a possible means of monitoring water vapor content because of problems that would necessarily be encountered in calibration of a sampling chamber which would have to operate at pressures many orders of magnitude below the absorption path pressure.

Next, a spectral hygrometer technique based on the work of Fowle[27] was investigated. This technique was used successfully by Low[28] but did

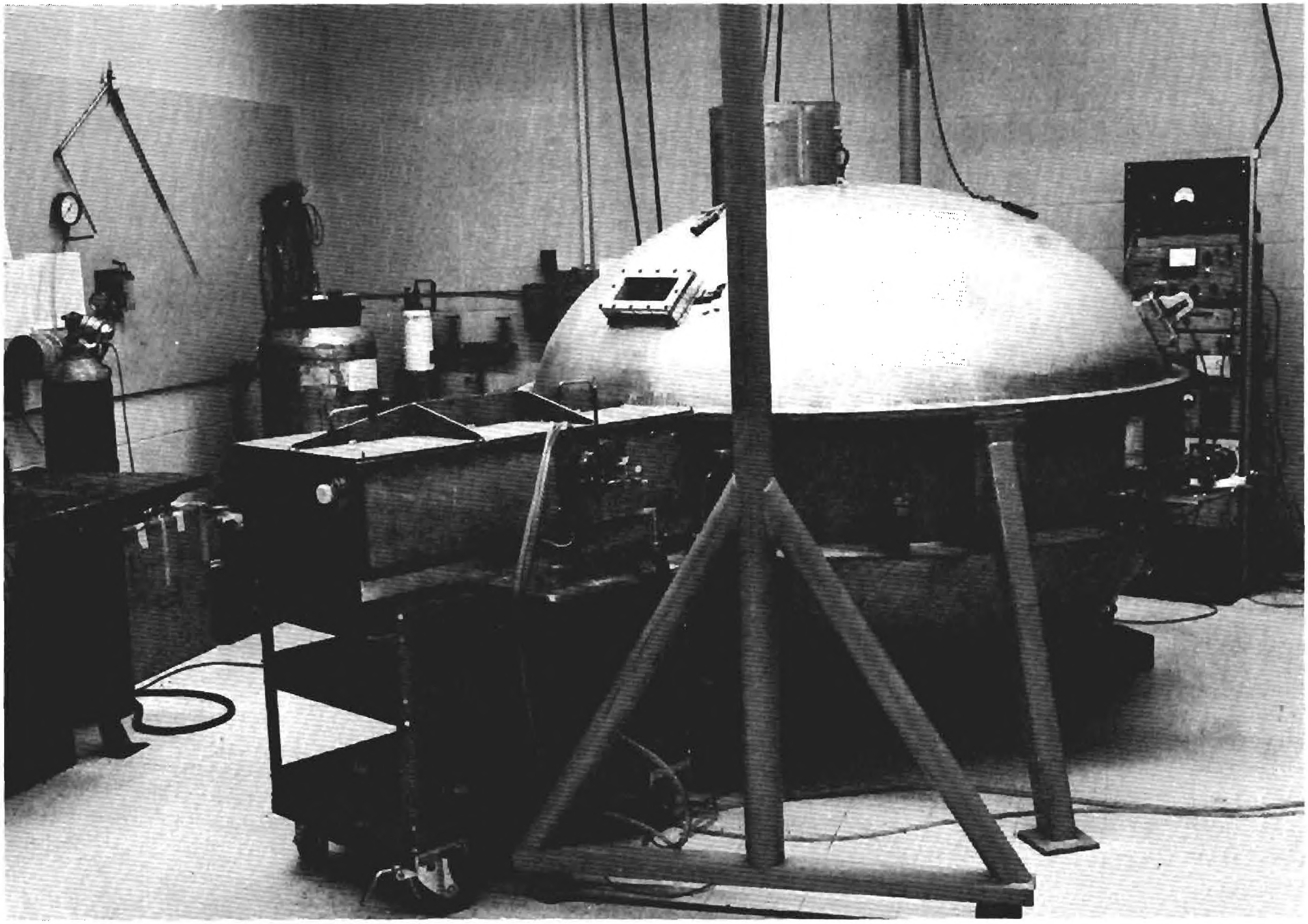

Figure 3. Multiple Reflection Chamber from Source Optics Side as Attached to Main Spectrometer Chamber.

not appear applicable to our absorption chamber, which has a physical length of 42 inches. The technique was based on comparison of one of the infrared absorption bands of water vapor with a nearby spectral window. Low's instrument used the absorption band near 0.93 microns. The response of this technique was shown to be quite good if the path is long so that the value of precipitable centimeters of water vapor, w, is likely to be between 0.1 and 3.0. For this auxiliary chamber, even at 100% relative humidity and normal temperature and pressure, $w \ll 0.1$, which makes the technique much less accurate than dew point techniques.

Gjessing, Holm, and Lanes[29] recently reported a technique accurate enough to resolve changes of 0.05% relative humidity at normal conditions by using a hygroscopically coated quartz crystal in an oscillator coupled to a mixer circuit. Two crystals of almost identical characteristics are chosen and one of these is plated with $SiO_x$. Each is put in an oscillator circuit with the $SiO_x$ coated crystal mounted in the region whose humidity is to be monitored, and the other serves as a reference. The difference frequency is monitored on a counter taking the output from the mixer. This difference frequency is a measure of humidity, and sensitivity of 6.5 Hz/per cent relative humidity seems typical for their unit.

Two transistor oscillators and a mixer circuit were built and the Physical Sciences Division of Georgia Tech prepared properly oriented $SiO_x$ plated quartz crystals to complete the instrument. The hydroscopic layer of $SiO_x$ flocculated after deposition and hence uncertainties existed as to hysteresis effect, response time, and absolute sensitivity of this humidity monitor. Measured sensitivity was only 0.7 Hz/per cent relative humidity at room temperature and pressure. Therefore, this technique was abandoned also, rather than spend the considerable time likely to be required to increase its sensitivity by a factor of ten.

A Cambridge Systems flow type dew point sensor was purchased next. This unit was guaranteed to give repeatable measurements within $\pm 0.5^{\circ}F$ over the range of $-40^{\circ}F$ to $+80^{\circ}F$.

Ultimately, chamber humidity data were obtained using four hygrometer techniques operating as follows:

1. The "Alluard" device allows one to measure the dew point by observing the temperature of a liquid when dew begins to form on the container walls. The liquid is cooled by evaporation brought about by bubbling air through the liquid.
2. The Cambridge Systems electronic hygrometer senses the formation of dew on a thermo-electrically cooled mirror, and maintains the mirror at the dew point by keeping a balance between the amount of light scattered by the dew and the light specularly reflected by the mirror surface.
3. The membrane hygrometer indicates the per cent relative humidity with a pointer whose position is controlled by the expansion or shrinkage of a membrane.
4. The sling psychrometer enables one to measure the relative humidity by measuring the temperature difference between wet- and dry-bulb thermometers.

Each set of data was converted to water vapor density in grams per cubic meter and averaged. From these data, one can get an idea of the reproducibility of the measurements from each device as well as an idea of the difference between measurements made with the various devices. The sling psychrometer was reproducible within ±0.5 $g/m^3$, but indicated a value about 1 $g/m^3$ higher than the average. The membrane device was reproducible within 1 $g/m^3$; however, its indication was always lower than the average, with the error increasing as the water vapor density decreased below 7 $g/m^3$. The electronic hygrometer showed the largest variation, and its average indication was about 0.5 $g/m^3$ above the average indication of the four devices. The "Alluard" device yielded readings 0.5 $g/m^3$ below the average of the readings.

Completion of these comparisons led to taking water vapor density as the average of measurements with all four of the above devices for each data run on the spectrometer.

## IV. Experimental Data

As mentioned in Section III, the data reported herein was calculated from interferograms which were recorded with the interference spectrometer while atmospheric conditions in the auxiliary chamber were carefully monitored. In most measurements reported here, the auxiliary chamber was adjusted for approximately a ten meter path length.

The numerical integration required to calculate the power spectra from the recorded interferograms used a triangular weighting function which gives a window function of the form

$$A_2(\nu) = L\left[\frac{\sin(\pi\nu L/c)}{\pi\nu L/c}\right]^2 \qquad (1)$$

where L = total path length change, $\nu$ = frequency, and c = free space velocity of light.

The resolution bandwidth for power spectra calculated with this weighting function is given by

$$\Delta\nu = \frac{C}{L}\ (\mathrm{Hz}) = \frac{1}{L}\ \mathrm{cm}^{-1} \qquad (2)$$

Equation (2) represents a two to one increase over the resolution bandwidth which would be obtained if the triangular weighting function was not used, but the sidelobes of the window function obtained from the triangular weighting function are about six per cent of the main peak rather than the twenty-five per cent side lobes which would be present if the triangular weighting function were not used.

The data to be reported here will be presented in two sections: first, the 15 $\mathrm{cm}^{-1}$ to 50 $\mathrm{cm}^{-1}$ data recorded while using the $4^{\circ}$K liquid helium cooled detector will be presented; then, the more recent 36 $\mathrm{cm}^{-1}$ to 100 $\mathrm{cm}^{-1}$ data using the $2^{\circ}$K detector.

The attenuation spectrum shown in Figure 4 is the average of ten individual attenuation spectra which were obtained under similar experimental conditions. Data used in plotting this spectrum are shown in Table I of the Appendix. The path length used in the auxiliary chamber was 10.4 meters for each spectrum. Also, a 60 rpm drive motor, a one sample per second detection time constant, a 300-to-1 gear reduction and a 0.0625 inch per revolution interferometer screw drive were used in each case. The resolution bandwidth for each spectrum was 0.27 $\mathrm{cm}^{-1}$.

Fifty per cent confidence limits have been calculated for the atmospheric absorption spectrum shown in Figure 4. These limits are illustrated in Figures 5, 6, and 7, which show expanded portions of the

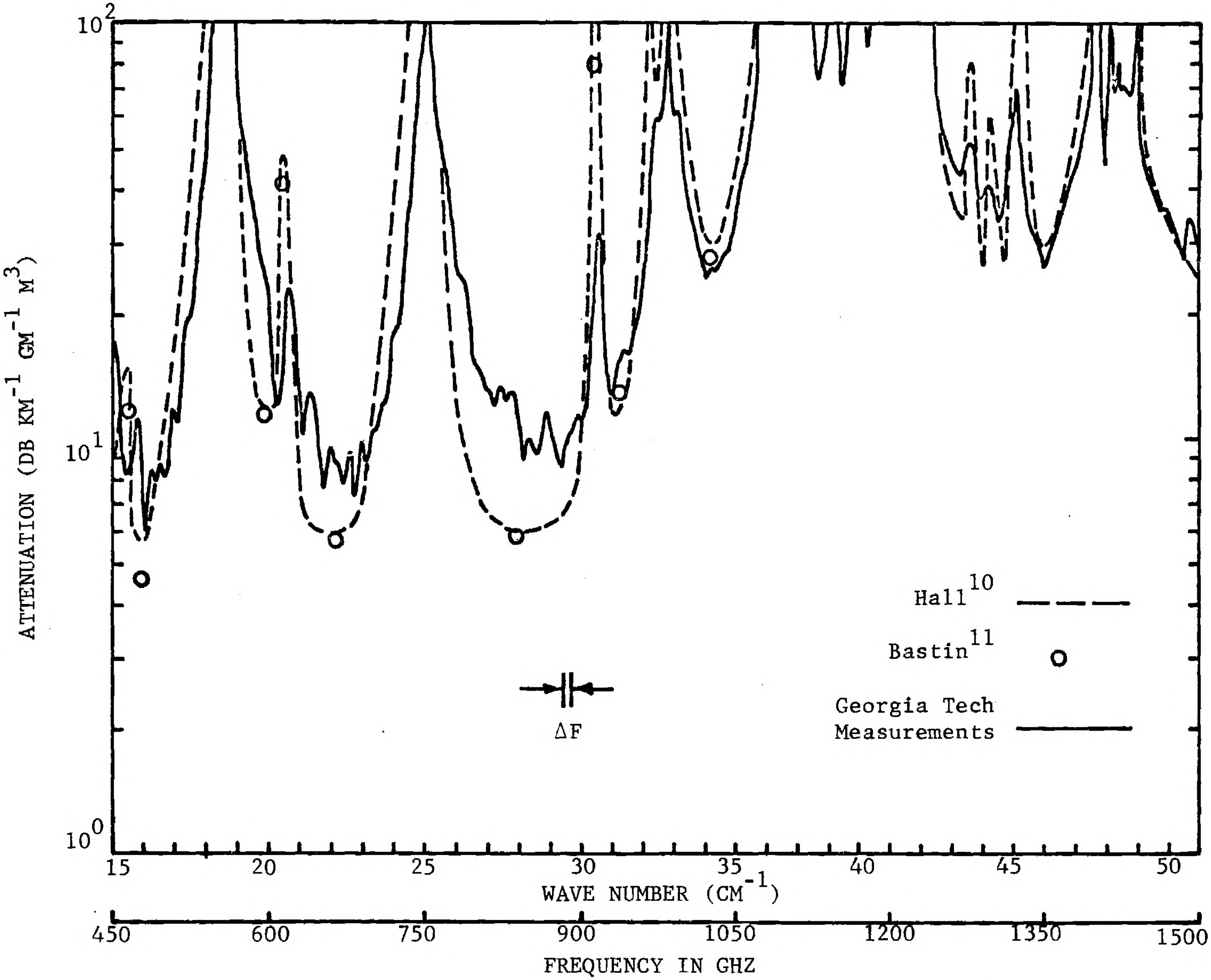


Figure 4. Average of Ten Normalized Atmospheric Attenuation Spectra for Normal Room Atmospheric Conditions (742 Torr, 22° C)

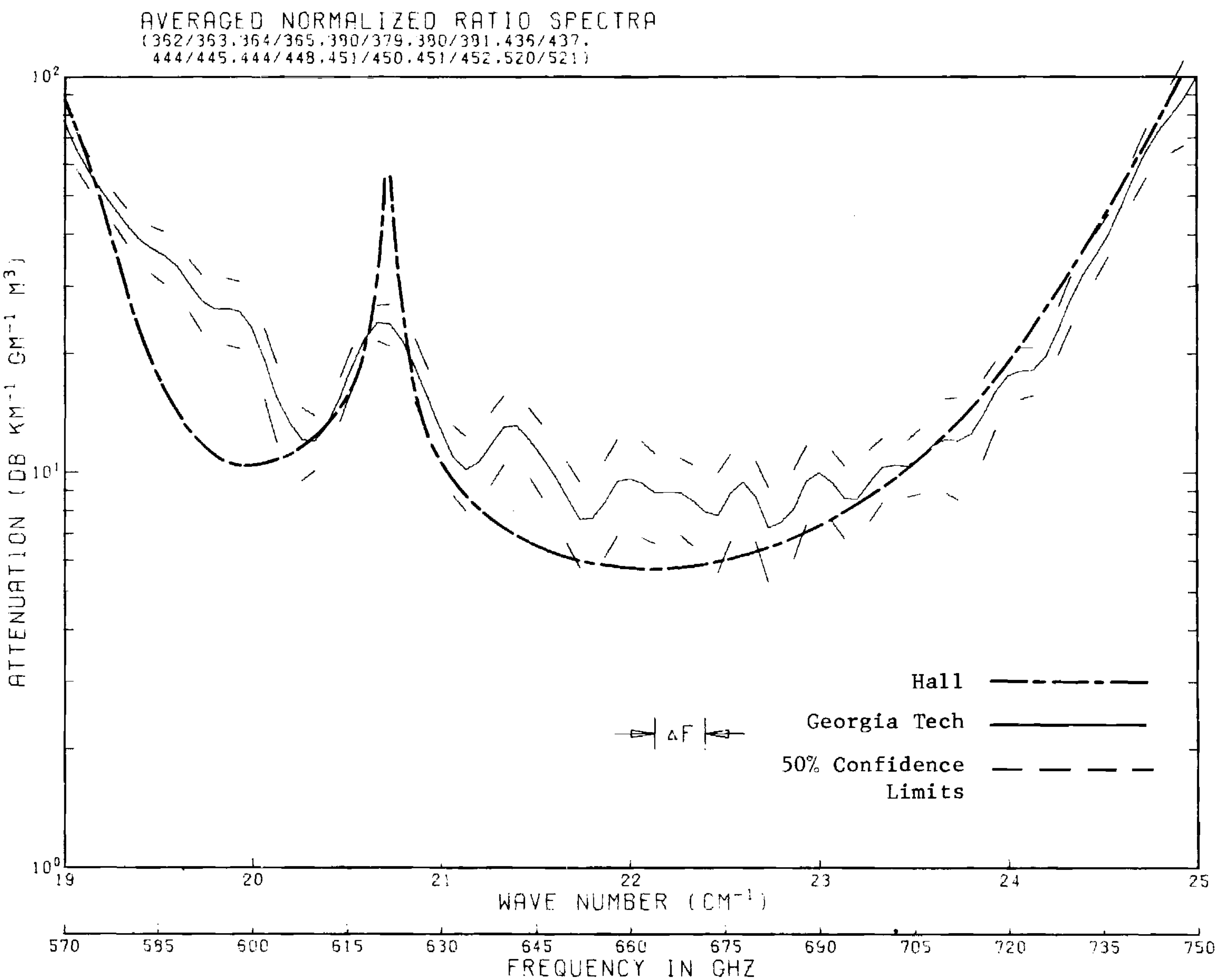


Figure 5. Average of Ten Normalized Atmospheric Attenuation Spectra for Normal Room Atmospheric Conditions (742 Torr, 22°C)

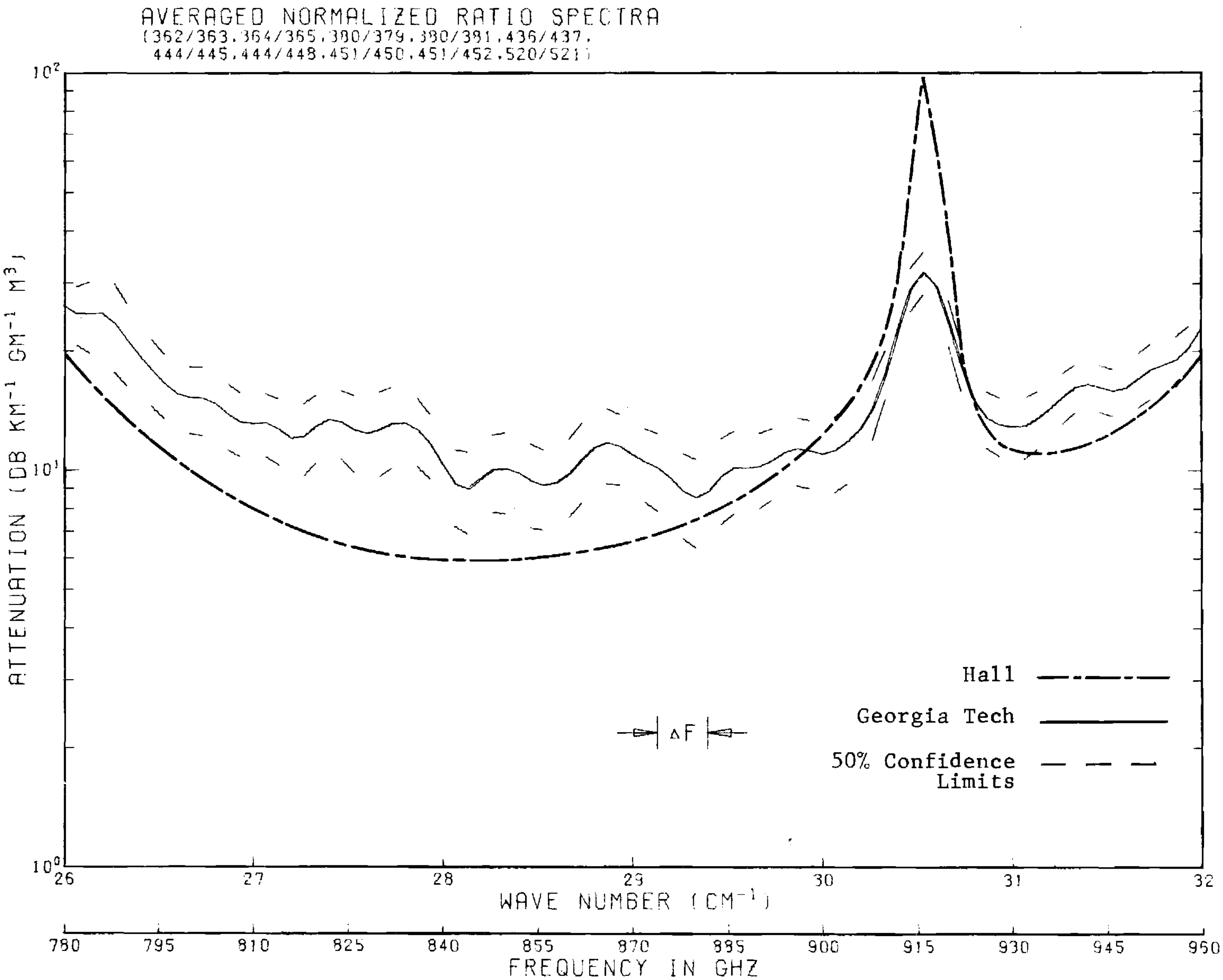


Figure 6. Average of Ten Normalized Atmospheric Attenuation Spectra for Normal Room Atmospheric Conditions (742 Torr, 22°C)

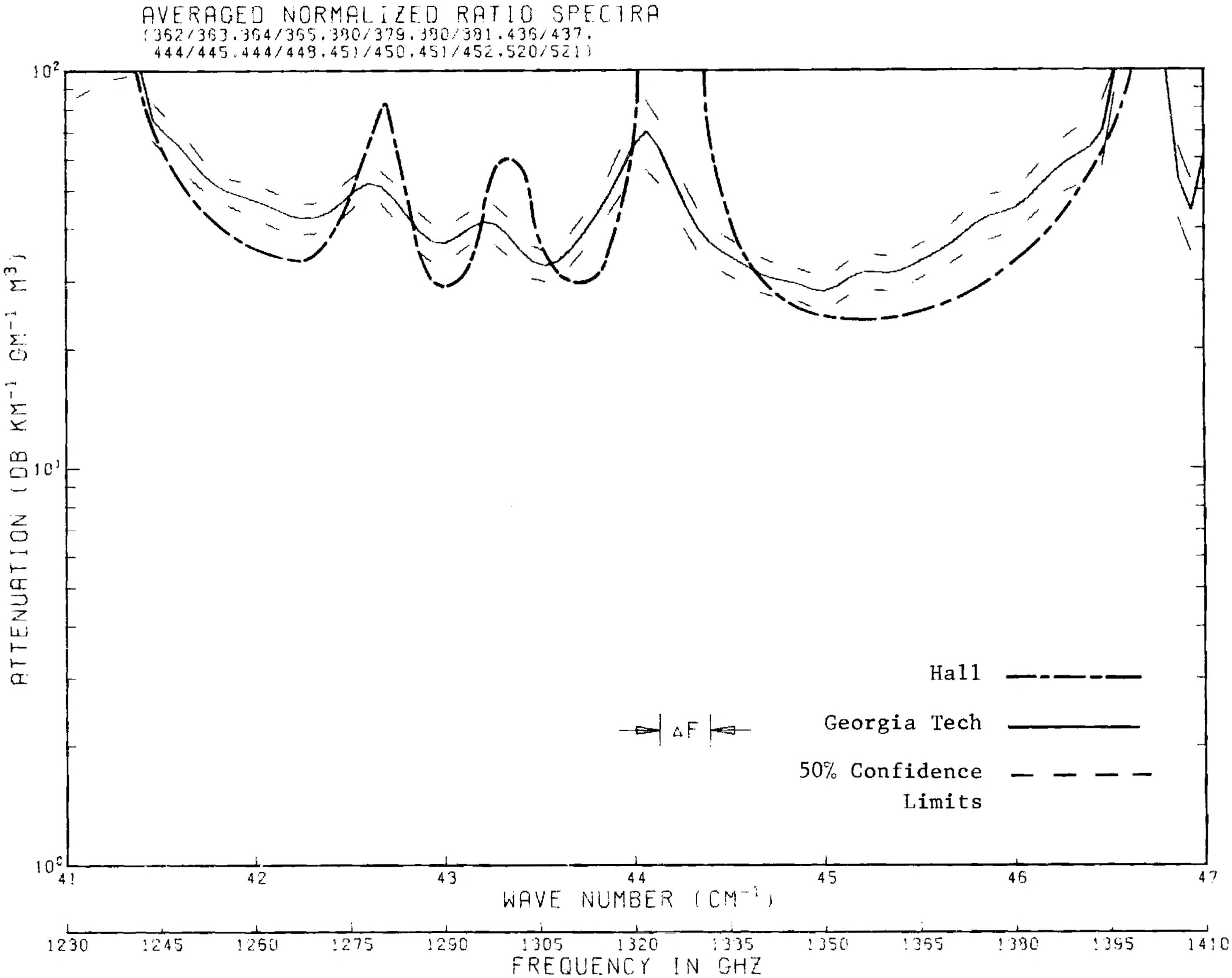


Figure 7. Average of Ten Normalized Atmospheric Attenuation Spectra for Normal Room Atmospheric Conditions (742 Torr, 22° C)

spectrum. Also shown in these figures are the results of calculations made by Hall.[10] The calculation of the confidence limits was based on the ten data sets using a Student's "t" distribution.

The expression for the intervals is:

$$\bar{x} - \frac{k}{\sqrt{n}} s < \mu < \bar{x} + \frac{k}{\sqrt{n}} s \quad ,$$

where

$\bar{x}$ is the average value of the ten absorption spectra at a particular frequency,

k is 0.70 for ten samples and a 50% confidence level. The value of k is obtained from an integration of the "t" distribution,

s is the sample standard deviation,

$$s = \left| \frac{\sum_i (x_i - \bar{x})^2}{n - 1} \right|^{\frac{1}{2}}$$

n is 10, the number of absorption spectra, and

$\mu$ is the actual mean value of absorption.

The attenuation spectrum shown in Figure 8 is the average of three individual attenuation spectra which were obtained under similar experimental conditions using the $2^{\circ}$K detector. Data used in graphing this spectrum are shown in Table II of the Appendix. For these spectra, the path length in the auxiliary chamber was maintained at 10.4 meters. The individual attenuation spectra are ratios of spectra which were recorded with the auxiliary chamber at less than 30 microns of mercury

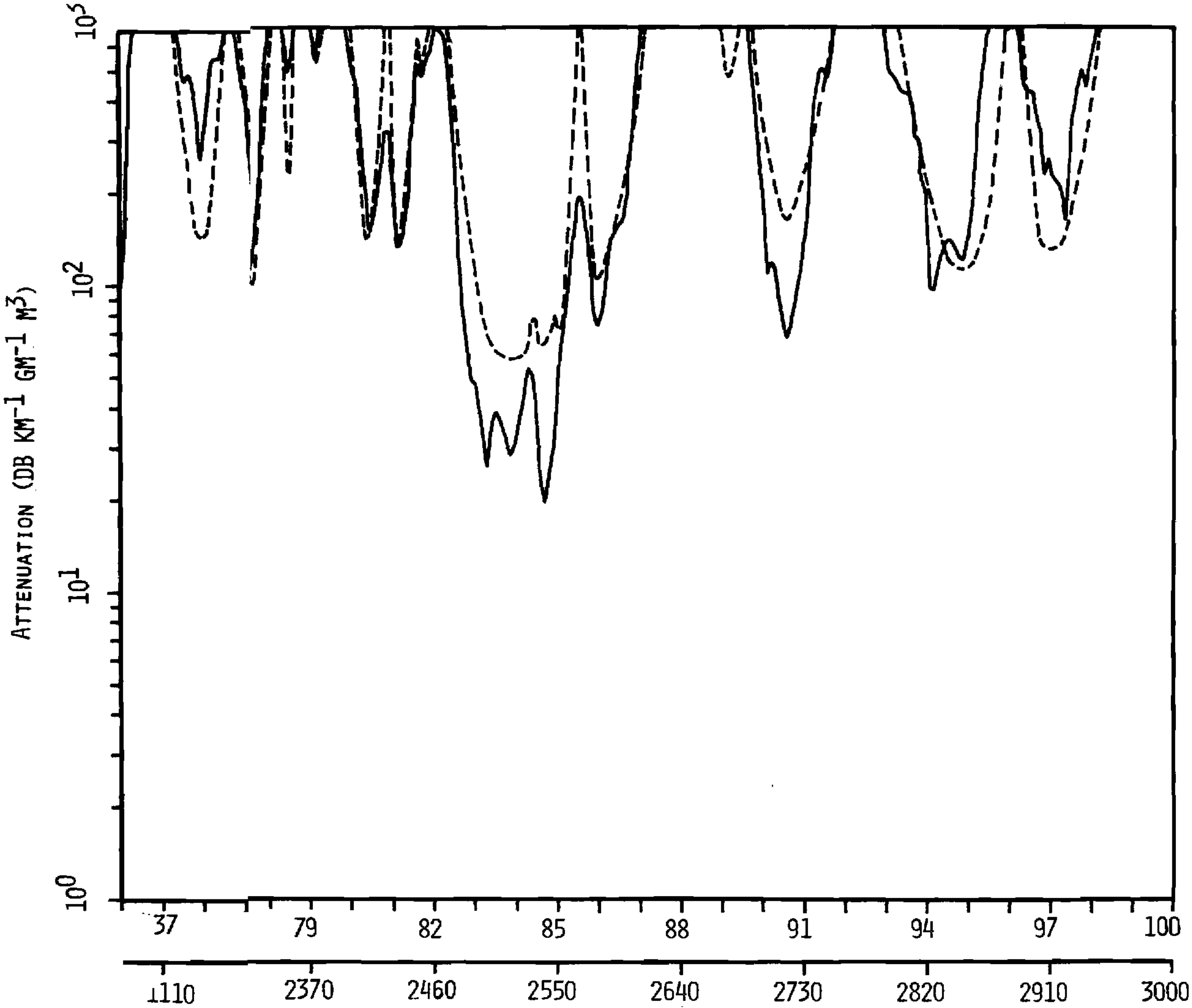


FIGURE 8. ATTENUATION SPECTRUM

and with the auxiliary chamber at 265 Torr. Measurements were made at 265 Torr rather than one atmosphere, as in previous measurements, so that the attenuation in the auxiliary chamber would be at a level which was within the dynamic range of the spectrometer. No attempt has been made to measure the effects of varying pressure on the line breadth constants, and the 0.5 $cm^{-1}$ resolution for these measurements is not adequate to make any conclusions.

A 25 rpm motor was used to drive the interferometer mirror in recording interferograms for the above measurements at $2^{\circ}K$. The gear reduction provided a $0.208333 \times 10^{-3}$ inch mirror displacement per data point, and the total mirror displacement was sufficient to provide a resolution bandwidth of 0.2 $cm^{-1}$. The power spectra were then calculated in frequency intervals of 0.1 $cm^{-1}$, and each point in the power spectrum was averaged with the two neighboring points on each side of it; thus giving a resolution bandwidth of less than 0.5 $cm^{-1}$.

The center frequencies of the water vapor absorption lines shown in Figure 8 and the corresponding transitions are shown in Table I. Also, these measured center frequencies in the 18 - 96 $cm^{-1}$ region are compared with values calculated by Hall,[10] Bastin,[11] Yunker and Querfeld,[8] Ghosh and Edwards,[5] and Zhevakin and Naumov.[12,13]

Table I

MEASURED AND PREDICTED VALUES FOR CENTER FREQUENCIES OF WATER VAPOR ABSORPTION LINES IN THE 18 - 96 $cm^{-1}$ FREQUENCY BAND

| Transition | Measured Frequency ($cm^{-1}$) | Predicted | | | | | |
|---|---|---|---|---|---|---|---|
| | | Ref. 10 | Ref. 11 | Ref. 8 | Ref. 5 | Ref. 30 | Ref. 12,13 |
| Pressure: 746 Torr | | | | | | | |
| $1_{-1} \rightarrow 1_{1}$ | 18.5 | 18.6 | 18.5 | 18.6 | 18.6 | 18.6 | 18 |
| $4_{3} \rightarrow 5_{1}$ | 20.7 | 20.7 | 20.5 | 20.6 | 20.6 | ---- | 21 |
| $8_{8} \rightarrow 9_{4}$, $8_{7} \rightarrow 9_{5}$ | 21.4 | ---- | ---- | 21.7 | 21.4 | 21.5 | -- |
| $2_{-2} \rightarrow 2_{0}$ | 25.1 | 25.1 | 25.0 | 25.1 | 25.1 | 25.1 | 25 |
| $3_{2} \rightarrow 4_{0}$ | 30.5 | 30.5 | 30.5 | 30.5 | 30.4 | 30.6 | 29 |
| $4_{2} \rightarrow 5_{-2}$ | 32.4 | 32.3 | 32.0 | 32.3 | 32.0 | ---- | 32 |
| $1_{0} \rightarrow 2_{-2}$ | 32.8 | 33.0 | 33.0 | 32.9 | 32.9 | 33.0 | 33 |
| Pressure: 265 Torr | | | | | | | |
| $0_{0} \rightarrow 1_{0}$ | 37.2 | 37.2 | 37.0 | 37.1 | 37.1 | 37.1 | 37 |
| $3_{-1} \rightarrow 3_{1}$ | 38.6 | 38.8 | | 38.8 | 38.7 | 38.8 | 38 |
| $4_{-2} \rightarrow 4_{0}$ | 40.2 | 40.3 | | 40.2 | 40.4 | | 40 |
| $2_{0} \rightarrow 2_{2}$ | 40.9 | 41.1 | | 41.0 | 40.9 | | 41 |
| $6_{3} \rightarrow 7_{1}$ | 42.6 | 42.6 | | 42.6 | 40.9 | | 42 |
| $7_{-1} \rightarrow 8_{-5}$ | 43.1 | 43.3 | | 43.3 | 43.1 | | 43 |
| $5_{1} \rightarrow 6_{-3}$ | 44.0 | 44.2 | | 44.1 | 44.1 | | 44 |
| $5_{-3} \rightarrow 5_{-1}$ | 46.9 | 47.2 | | 47.0 | 46.9 | | 47 |
| $5_{2} \rightarrow 6_{0}$ | 51.4 | 51.5 | | 51.4 | 51.3 | | 51 |
| $4_{-4} \rightarrow 4_{-2}$ | 53.3 | 53.5 | | 53.4 | 53.3 | | 53 |

Table I (Continued)

| Transition | Measured Frequency ($cm^{-1}$) | Ref. 10 | Ref. 11 | Predicted Ref. 8 | Ref. 5 | Ref. 30 | Ref. 12,13 |
|---|---|---|---|---|---|---|---|
| $2_{-1} \rightarrow 2_{1}$ | 55.4 | 55.8 | | 55.4 | 55.4 | | 55 |
| $1_{-1} \rightarrow 2_{-1}$ | | | | 55.7 | 55.7 | | 56 |
| $6_{-2} \rightarrow 6_{0}$ | 58.8 | 59.0 | | 58.9 | 58.8 | | 59 |
| $6_{-4} \rightarrow 6_{-2}$ | 59.7 | 59.9 | | 59.8 | 59.9 | | 60 |
| $7_{-3} \rightarrow 7_{-1}$ | | | | 60.0 | 50.0 | | |
| $5_{-1} \rightarrow 5_{1}$ | 62.1 | 62.3 | | 62.3 | 62.4 | | 62 |
| $3_{-2} \rightarrow 3_{0}$ | 63.8 | 64.1 | | 64.0 | 64.0 | | 64 |
| $8_{-4} \rightarrow 8_{-2}$ | 67.1 | 67.1 | | 67.1 | ---- | | -- |
| $4_{0} \rightarrow 4_{2}$ | 67.9 | 68.2 | | 68.1 | 68.2 | | -- |
| $3_{0} \rightarrow 4_{-2}$ | 69.0 | 69.2 | | 69.2 | 68.8 | | 69 |
| $2_{-2} \rightarrow 3_{-2}$ | 72.0 | 72.3 | | 72.2 | 72.2 | | 72 |
| $7_{2} \rightarrow 8_{0}$ | | | | | | | |
| $3_{1} \rightarrow 3_{3}$ | 73.2 | 73.3 | | 73.2 | 73.3 | | 73 |
| $5_{-5} \rightarrow 5_{-3}$ | 73.9 | 74.0 | | 74.1 | 74.1 | | 74 |
| $4_{-3} \rightarrow 4_{-1}$ | 75.5 | 75.6 | | 75.6 | 75.6 | | 76 |
| $9_{-3} \rightarrow 9_{-1}$ | 77.2 | 77.5 | | 77.5 | 77.5 | | 78 |
| $10_{-4} \rightarrow 10_{-2}$ | 78.1 | 78.2 | | 78.2 | 75.7 | | 78 |
| $7_{-5} \rightarrow 7_{-3}$ | | | | 78.2 | 78.1 | | |
| $3_{0} \rightarrow 3_{2}$ | 78.8 | 79.0 | | 79.0 | 78.9 | | 79 |
| $3_{-2} \rightarrow 4_{-4}$ | 79.5 | 79.8 | | 79.8 | 79.6 | | 80 |
| $9_{-5} \rightarrow 9_{-3}$ | 80.8 | 80.9 | | 81.0 | 80.9 | | 81 |

Table I (Continued)

| Transition | Measured Frequency ($cm^{-1}$) | Predicted Ref. 10 | Ref. 11 | Ref. 8 | Ref. 5 | Ref. 30 | Ref. 12, 13 |
|---|---|---|---|---|---|---|---|
| $4_{-1} \rightarrow 4_{1}$ | 82.0 | 82.2 | | 82.1 | 82.1 | | 82 |
| $8_{0} \rightarrow 9_{-4}$ | 84.3 | 84.5 | | 84.5 | 84.4 | | 84 |
| $6_{1} \rightarrow 7_{-1}$ | | | | 85.6 | 85.3 | | |
| $9_{-1} \rightarrow 10_{-5}$ | 85.6 | 85.6 | | 85.7 | 85.7 | | 86 |
| $11_{-5} \rightarrow 11_{-3}$ | | | | 85.7 | 87.3 | | |
| $3_{-3} \rightarrow 4_{-3}$ | 88.1 | 88.1 | | 88.1 | 87.9 | | 88 |
| $1_{1} \rightarrow 2_{1}$ | 92.7 | 92.6 | | 92.5 | 92.5 | | 92 |
| $6_{-3} \rightarrow 6_{-1}$ | 96.0 | | | 96.0 | 96.0 | | 96 |
| $6_{0} \rightarrow 6_{2}$ | | | | 96.2 | 96.1 | | |

## V. Conclusions

The data thus allow several conclusions to be drawn with regard to water vapor absorption in the 10 $cm^{-1}$ to 100 $cm^{-1}$ frequency region. (1) The theoretical calculations of Hall[10] give a representative picture of the "windows" throughout this part of the spectrum although, in some cases, measured attenuation seems to run higher than predicted. (2) There are no apparent "windows" or "holes" in this region which are "miraculously" lower in absorption magnitude than modifications and extensions of the Van Vleck theory predict. (3) Measured line center frequencies are in excellent agreement with predictions previously available. (4) The severe attenuation of water vapor in this region of the spectrum limits applications to: (a) laboratory studies; (b) limited range, secure systems; (c) high altitude or extra-terrestrial systems if long range is required. (5) Studies of other gases, for example, oxygen, the nitric oxides, and ozone, which also have absorption lines in the 10 $cm^{-1}$ to 100 $cm^{-1}$ region, should be undertaken if applications mentioned in (4b) and (4c) are to be given serious consideration.

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# VII. APPENDIX

TABLE I

DATA USED IN PLOTTING SPECTRUM SHOWN IN FIGURE 4

AVERAGED NORMALIZED RATIO SPECTRA

(362/363,364/365,380/379,380/381,436/437,
444/443,444/448,451/450,451/452,520/521)

| FREQUENCY (GHZ) | RECIPROCAL CENTIMETER | LOWER CONFIDENCE LIMIT | DB/KMG/M3 | UPPER CONFIDENCE LIMIT |
|---|---|---|---|---|
| 450. | 15.000 | 18.46 | 21.69 | 24.92 |
| 452. | 15.067 | 14.87 | 17.93 | 20.99 |
| 454. | 15.133 | 12.49 | 15.57 | 18.66 |
| 456. | 15.200 | 11.17 | 14.15 | 17.14 |
| 458. | 15.267 | 9.68 | 12.21 | 14.74 |
| 460. | 15.333 | 7.90 | 9.77 | 11.63 |
| 462. | 15.400 | 6.60 | 8.19 | 9.78 |
| 464. | 15.467 | 6.51 | 8.14 | 9.77 |
| 466. | 15.533 | 6.41 | 8.21 | 10.01 |
| 468. | 15.600 | 6.30 | 8.24 | 10.18 |
| 470. | 15.667 | 6.97 | 8.96 | 10.96 |
| 472. | 15.733 | 8.13 | 10.25 | 12.36 |
| 474. | 15.800 | 9.29 | 11.46 | 13.64 |
| 476. | 15.867 | 9.00 | 11.12 | 13.24 |
| 478. | 15.933 | 6.87 | 8.88 | 10.88 |
| 480. | 16.000 | 5.04 | 6.83 | 8.62 |
| 482. | 16.067 | 3.79 | 5.64 | 7.49 |
| 484. | 16.133 | 5.05 | 7.12 | 9.19 |
| 486. | 16.200 | 5.97 | 8.37 | 10.77 |
| 488. | 16.267 | 5.86 | 8.36 | 10.86 |
| 490. | 16.333 | 5.61 | 7.94 | 10.26 |
| 492. | 16.400 | 5.70 | 7.80 | 9.89 |
| 494. | 16.467 | 6.65 | 8.58 | 10.51 |
| 496. | 16.533 | 6.50 | 8.75 | 10.99 |
| 498. | 16.600 | 6.30 | 8.61 | 10.93 |
| 500. | 16.667 | 5.87 | 8.00 | 10.14 |
| 502. | 16.733 | 6.05 | 8.09 | 10.14 |
| 504. | 16.800 | 7.50 | 9.39 | 11.28 |
| 506. | 16.867 | 9.49 | 11.36 | 13.24 |
| 508. | 16.933 | 9.72 | 11.93 | 14.14 |
| 510. | 17.000 | 8.52 | 10.96 | 13.40 |
| 512. | 17.067 | 8.03 | 10.53 | 13.03 |
| 514. | 17.133 | 8.55 | 11.36 | 14.18 |
| 516. | 17.200 | 9.81 | 13.07 | 16.34 |
| 518. | 17.267 | 11.65 | 15.39 | 18.93 |
| 520. | 17.333 | 14.27 | 17.71 | 21.15 |
| 522. | 17.400 | 16.29 | 19.33 | 22.37 |

TABLE I (CONTINUED)

| FREQUENCY (GHZ) | RECIPROCAL CENTIMETER | LOWER CONFIDENCE LIMIT | DB/KMG/M3 | UPPER CONFIDENCE LIMIT |
|---|---|---|---|---|
| 524. | 17.467 | 16.66 | 19.70 | 22.72 |
| 526. | 17.533 | 16.30 | 19.69 | 23.08 |
| 528. | 17.600 | 17.21 | 20.99 | 24.77 |
| 530. | 17.667 | 20.08 | 24.23 | 28.38 |
| 532. | 17.733 | 24.25 | 28.68 | 33.10 |
| 534. | 17.800 | 28.50 | 33.25 | 38.01 |
| 536. | 17.867 | 32.29 | 37.60 | 42.91 |
| 538. | 17.933 | 37.23 | 43.24 | 49.26 |
| 540. | 18.000 | 44.80 | 51.96 | 59.13 |
| 542. | 18.067 | 54.15 | 62.96 | 71.77 |
| 544. | 18.133 | 64.66 | 77.48 | 90.28 |
| 546. | 18.200 | - | * | - |
| 548. | 18.267 | - | * | - |
| 550. | 18.333 | - | * | - |
| 552. | 18.400 | - | * | - |
| 554. | 18.467 | - | * | - |
| 556. | 18.533 | - | * | - |
| 558. | 18.600 | - | * | - |
| 560. | 18.667 | - | * | - |
| 562. | 18.733 | - | * | - |
| 564. | 18.800 | - | * | - |
| 566. | 18.867 | - | * | - |
| 568. | 18.933 | - | * | - |
| 570. | 19.000 | 65.62 | 77.34 | 89.06 |
| 572. | 19.067 | 58.24 | 65.18 | 72.13 |
| 574. | 19.133 | 51.96 | 57.32 | 62.68 |
| 576. | 19.200 | 46.76 | 51.43 | 56.07 |
| 578. | 19.267 | 42.21 | 46.49 | 50.78 |
| 580. | 19.333 | 37.83 | 42.15 | 46.48 |
| 582. | 19.400 | 34.16 | 38.81 | 43.46 |
| 584. | 19.467 | 31.76 | 36.79 | 41.80 |
| 586. | 19.533 | 30.09 | 35.37 | 40.65 |
| 588. | 19.600 | 28.28 | 33.30 | 38.31 |
| 590. | 19.667 | 25.36 | 29.92 | 34.47 |
| 592. | 19.733 | 22.66 | 27.13 | 31.59 |
| 594. | 19.800 | 21.15 | 25.88 | 30.61 |
| 596. | 19.867 | 21.00 | 25.93 | 30.87 |
| 598. | 19.933 | 20.61 | 25.50 | 30.39 |
| 600. | 20.000 | 18.63 | 23.11 | 27.60 |
| 602. | 20.067 | 15.31 | 19.22 | 23.13 |
| 604. | 20.133 | 11.86 | 15.33 | 18.80 |
| 606. | 20.200 | 10.31 | 13.30 | 16.29 |

* - BEYOND SENSITIVITY OF INSTRUMENT

TABLE I (CONTINUED)

| FREQUENCY (GHZ) | RECIPROCAL CENTIMETER | LOWER CONFIDENCE LIMIT | DB/KMG/M3 | UPPER CONFIDENCE LIMIT |
|---|---|---|---|---|
| 608. | 20.267 | 9.52 | 12.04 | 14.57 |
| 610. | 20.333 | 10.06 | 11.99 | 13.93 |
| 612. | 20.400 | 11.44 | 13.18 | 14.91 |
| 614. | 20.467 | 13.40 | 15.43 | 17.46 |
| 616. | 20.533 | 16.31 | 18.60 | 20.90 |
| 618. | 20.600 | 19.47 | 21.83 | 24.20 |
| 620. | 20.667 | 21.44 | 23.93 | 26.42 |
| 622. | 20.733 | 20.89 | 23.74 | 26.59 |
| 624. | 20.800 | 18.15 | 21.44 | 24.74 |
| 626. | 20.867 | 15.02 | 18.35 | 21.68 |
| 628. | 20.933 | 12.53 | 15.38 | 18.23 |
| 630. | 21.000 | 10.48 | 12.85 | 15.22 |
| 632. | 21.067 | 8.68 | 10.89 | 13.10 |
| 634. | 21.133 | 7.98 | 10.15 | 12.33 |
| 636. | 21.200 | 8.34 | 10.60 | 12.86 |
| 638. | 21.267 | 9.31 | 11.77 | 14.23 |
| 640. | 21.333 | 10.44 | 13.02 | 15.60 |
| 642. | 21.400 | 10.59 | 13.15 | 15.71 |
| 644. | 21.467 | 9.68 | 12.11 | 14.55 |
| 646. | 21.533 | 8.63 | 10.93 | 13.23 |
| 648. | 21.600 | 7.67 | 9.85 | 12.03 |
| 650. | 21.667 | 6.62 | 8.64 | 10.65 |
| 652. | 21.733 | 5.74 | 7.60 | 9.46 |
| 654. | 21.800 | 5.74 | 7.65 | 9.56 |
| 656. | 21.867 | 6.10 | 8.39 | 10.69 |
| 658. | 21.933 | 6.90 | 9.50 | 12.10 |
| 660. | 22.000 | 6.91 | 9.64 | 12.38 |
| 662. | 22.067 | 6.82 | 9.39 | 11.96 |
| 664. | 22.133 | 6.61 | 8.89 | 11.18 |
| 666. | 22.200 | 6.88 | 8.92 | 10.96 |
| 668. | 22.267 | 6.95 | 8.90 | 10.87 |
| 670. | 22.333 | 6.52 | 8.50 | 10.48 |
| 672. | 22.400 | 5.89 | 7.95 | 10.01 |
| 674. | 22.467 | 5.59 | 7.78 | 9.98 |
| 676. | 22.533 | 6.66 | 8.88 | 11.08 |
| 678. | 22.600 | 7.32 | 9.46 | 11.60 |
| 680. | 22.667 | 6.65 | 8.65 | 10.64 |
| 682. | 22.733 | 5.27 | 7.22 | 9.17 |
| 684. | 22.800 | 5.59 | 7.49 | 9.39 |
| 686. | 22.867 | 6.06 | 8.12 | 10.19 |
| 688. | 22.933 | 7.37 | 9.53 | 11.70 |
| 690. | 23.000 | 7.88 | 9.99 | 12.11 |

TABLE I (CONTINUED)

| FREQUENCY (GHZ) | RECIPROCAL CENTIMETER | LOWER CONFIDENCE LIMIT | DB/KMG/M3 | UPPER CONFIDENCE LIMIT |
|---|---|---|---|---|
| 692. | 23.067 | 7.54 | 9.43 | 11.32 |
| 694. | 23.133 | 6.80 | 8.61 | 10.41 |
| 696. | 23.200 | 6.65 | 8.55 | 10.45 |
| 698. | 23.267 | 7.51 | 9.46 | 11.42 |
| 700. | 23.333 | 8.43 | 10.32 | 12.21 |
| 702. | 23.400 | 8.71 | 10.44 | 12.17 |
| 704. | 23.467 | 8.69 | 10.38 | 12.07 |
| 706. | 23.533 | 8.86 | 10.91 | 12.95 |
| 708. | 23.600 | 9.10 | 11.76 | 14.42 |
| 710. | 23.667 | 8.91 | 12.14 | 15.38 |
| 712. | 23.733 | 8.56 | 12.05 | 15.54 |
| 714. | 23.800 | 9.15 | 12.54 | 15.93 |
| 716. | 23.867 | 10.78 | 13.99 | 17.19 |
| 718. | 23.933 | 12.95 | 16.04 | 19.13 |
| 720. | 24.000 | 14.67 | 17.61 | 20.56 |
| 722. | 24.067 | 15.39 | 18.07 | 20.76 |
| 724. | 24.133 | 15.65 | 18.19 | 20.73 |
| 726. | 24.200 | 17.00 | 19.67 | 22.33 |
| 728. | 24.267 | 19.94 | 23.04 | 26.14 |
| 730. | 24.333 | 23.63 | 27.46 | 31.29 |
| 732. | 24.400 | 27.32 | 31.76 | 36.21 |
| 734. | 24.467 | 30.80 | 35.54 | 40.27 |
| 736. | 24.533 | 35.01 | 39.95 | 44.88 |
| 738. | 24.600 | 41.22 | 46.75 | 52.27 |
| 740. | 24.667 | 48.76 | 55.63 | 62.50 |
| 742. | 24.733 | 55.67 | 64.84 | 74.00 |
| 744. | 24.800 | 60.84 | 73.12 | 85.41 |
| 746. | 24.867 | 64.17 | 79.81 | 95.45 |
| 748. | 24.933 | 66.83 | 88.15 | 109.46 |
| 750. | 25.000 | - | * | - |
| 752. | 25.067 | - | * | - |
| 754. | 25.133 | - | * | - |
| 756. | 25.200 | 67.45 | 89.08 | 110.72 |
| 758. | 25.267 | 62.39 | 75.99 | 89.59 |
| 760. | 25.333 | 57.08 | 65.98 | 74.88 |
| 762. | 25.400 | 51.72 | 58.09 | 64.46 |
| 764. | 25.467 | 47.12 | 52.05 | 56.99 |
| 766. | 25.533 | 44.21 | 48.28 | 52.35 |
| 768. | 25.600 | 42.13 | 46.06 | 49.98 |
| 770. | 25.667 | 39.35 | 43.49 | 47.63 |
| 772. | 25.733 | 35.52 | 39.94 | 44.36 |
| 774. | 25.800 | 31.23 | 35.82 | 40.41 |

* - BEYOND SENSITIVITY OF INSTRUMENT

TABLE I (CONTINUED)

| FREQUENCY (GHZ) | RECIPROCAL CENTIMETER | LOWER CONFIDENCE LIMIT | DB/KMG/M3 | UPPER CONFIDENCE LIMIT |
|---|---|---|---|---|
| 776. | 25.867 | 27.26 | 31.75 | 36.24 |
| 778. | 25.933 | 24.18 | 28.32 | 32.46 |
| 780. | 26.000 | 22.02 | 25.93 | 29.84 |
| 782. | 26.067 | 20.61 | 24.80 | 28.99 |
| 784. | 26.133 | 19.73 | 24.76 | 29.79 |
| 786. | 26.200 | 18.87 | 24.82 | 30.78 |
| 788. | 26.267 | 17.56 | 23.49 | 29.42 |
| 790. | 26.333 | 16.26 | 21.27 | 26.27 |
| 792. | 26.400 | 15.34 | 19.41 | 23.47 |
| 794. | 26.467 | 14.45 | 17.87 | 21.30 |
| 796. | 26.533 | 13.49 | 16.51 | 19.54 |
| 798. | 26.600 | 12.71 | 15.57 | 18.43 |
| 800. | 26.667 | 12.33 | 15.24 | 18.14 |
| 802. | 26.733 | 12.19 | 15.16 | 18.14 |
| 804. | 26.800 | 11.83 | 14.71 | 17.60 |
| 806. | 26.867 | 11.21 | 13.85 | 16.49 |
| 808. | 26.933 | 10.78 | 13.20 | 15.62 |
| 810. | 27.000 | 10.75 | 13.09 | 15.45 |
| 812. | 27.067 | 10.77 | 13.14 | 15.51 |
| 814. | 27.133 | 10.27 | 12.68 | 15.09 |
| 816. | 27.200 | 9.52 | 12.01 | 14.50 |
| 818. | 27.267 | 9.63 | 12.14 | 14.66 |
| 820. | 27.333 | 10.41 | 12.90 | 15.39 |
| 822. | 27.400 | 10.94 | 13.42 | 15.90 |
| 824. | 27.467 | 10.64 | 13.21 | 15.79 |
| 826. | 27.533 | 9.84 | 12.62 | 15.40 |
| 828. | 27.600 | 9.39 | 12.35 | 15.31 |
| 830. | 27.667 | 9.62 | 12.66 | 15.69 |
| 832. | 27.733 | 10.06 | 13.09 | 16.11 |
| 834. | 27.800 | 10.29 | 13.15 | 16.01 |
| 836. | 27.867 | 10.15 | 12.66 | 15.18 |
| 838. | 27.933 | 9.47 | 11.63 | 13.80 |
| 840. | 28.000 | 8.32 | 10.31 | 12.30 |
| 842. | 28.067 | 7.20 | 9.21 | 11.22 |
| 844. | 28.133 | 6.69 | 8.98 | 11.08 |
| 846. | 28.200 | 7.38 | 9.53 | 11.69 |
| 848. | 28.267 | 7.81 | 10.04 | 12.27 |
| 850. | 28.333 | 7.77 | 10.10 | 12.43 |
| 852. | 28.400 | 7.50 | 9.85 | 12.20 |
| 854. | 28.467 | 7.15 | 9.39 | 11.63 |
| 856. | 28.533 | 7.07 | 9.16 | 11.25 |
| 858. | 28.600 | 7.25 | 9.31 | 11.37 |

TABLE 1 (CONTINUED)

| FREQUENCY (GHZ) | RECIPROCAL CENTIMETER | LOWER CONFIDENCE LIMIT | DB/KMG/M3 | UPPER CONFIDENCE LIMIT |
|---|---|---|---|---|
| 860. | 28.667 | 7.60 | 9.79 | 11.99 |
| 862. | 28.733 | 8.26 | 10.67 | 13.09 |
| 864. | 28.800 | 8.86 | 11.43 | 14.00 |
| 866. | 28.867 | 9.25 | 11.76 | 14.28 |
| 868. | 28.933 | 9.16 | 11.51 | 13.84 |
| 870. | 29.000 | 8.74 | 10.95 | 13.17 |
| 872. | 29.067 | 8.29 | 10.50 | 12.70 |
| 874. | 29.133 | 7.89 | 10.13 | 12.38 |
| 876. | 29.200 | 7.34 | 9.56 | 11.79 |
| 878. | 29.267 | 6.72 | 8.86 | 11.00 |
| 880. | 29.333 | 6.40 | 8.53 | 10.65 |
| 882. | 29.400 | 6.61 | 8.86 | 11.10 |
| 884. | 29.467 | 7.30 | 9.67 | 12.04 |
| 886. | 29.533 | 7.76 | 10.15 | 12.54 |
| 888. | 29.600 | 7.84 | 10.15 | 12.45 |
| 890. | 29.667 | 8.02 | 10.21 | 12.40 |
| 892. | 29.733 | 8.40 | 10.56 | 12.73 |
| 894. | 29.800 | 8.90 | 11.08 | 13.27 |
| 896. | 29.867 | 9.15 | 11.34 | 13.54 |
| 898. | 29.933 | 8.99 | 11.19 | 13.38 |
| 900. | 30.000 | 8.75 | 11.00 | 13.26 |
| 902. | 30.067 | 8.79 | 11.21 | 13.63 |
| 904. | 30.133 | 9.24 | 11.83 | 14.42 |
| 906. | 30.200 | 10.15 | 12.73 | 15.32 |
| 908. | 30.267 | 11.91 | 14.34 | 16.77 |
| 910. | 30.333 | 15.10 | 17.58 | 20.06 |
| 912. | 30.400 | 19.92 | 22.86 | 25.80 |
| 914. | 30.467 | 25.13 | 28.70 | 32.27 |
| 916. | 30.533 | 27.67 | 31.53 | 35.39 |
| 918. | 30.600 | 25.49 | 29.12 | 32.74 |
| 920. | 30.667 | 20.51 | 23.60 | 26.69 |
| 922. | 30.733 | 15.79 | 18.38 | 20.97 |
| 924. | 30.800 | 12.72 | 15.03 | 17.34 |
| 926. | 30.867 | 11.35 | 13.54 | 15.73 |
| 928. | 30.933 | 10.84 | 13.03 | 15.22 |
| 930. | 31.000 | 10.66 | 12.69 | 15.12 |
| 932. | 31.067 | 10.66 | 12.94 | 15.22 |
| 934. | 31.133 | 11.27 | 13.52 | 15.78 |
| 936. | 31.200 | 12.11 | 14.34 | 16.57 |
| 938. | 31.267 | 13.12 | 15.32 | 17.52 |
| 940. | 31.333 | 13.96 | 16.18 | 18.40 |
| 942. | 31.400 | 14.25 | 16.56 | 18.74 |

## TABLE I (CONTINUED)

| FREQUENCY (GHZ) | RECIPROCAL CENTIMETER | LOWER CONFIDENCE LIMIT | DB/KMG/M3 | UPPER CONFIDENCE LIMIT |
|---|---|---|---|---|
| 944. | 31.467 | 14.01 | 16.19 | 18.38 |
| 946. | 31.533 | 13.70 | 15.85 | 17.99 |
| 948. | 31.600 | 13.60 | 16.12 | 18.45 |
| 950. | 31.667 | 14.38 | 17.02 | 19.65 |
| 952. | 31.733 | 15.04 | 17.93 | 20.83 |
| 954. | 31.800 | 15.55 | 18.46 | 21.37 |
| 956. | 31.867 | 16.20 | 18.95 | 21.71 |
| 958. | 31.933 | 17.65 | 20.36 | 23.06 |
| 960. | 32.000 | 19.92 | 22.94 | 25.95 |
| 962. | 32.067 | 22.99 | 26.58 | 30.16 |
| 964. | 32.133 | 27.12 | 31.40 | 35.67 |
| 966. | 32.200 | 32.51 | 37.73 | 42.96 |
| 968. | 32.267 | 38.78 | 45.56 | 52.33 |
| 970. | 32.333 | 44.85 | 53.74 | 62.63 |
| 972. | 32.400 | 48.00 | 58.40 | 68.86 |
| 974. | 32.467 | 48.14 | 58.07 | 68.01 |
| 976. | 32.533 | 48.58 | 57.78 | 66.98 |
| 978. | 32.600 | 51.26 | 60.76 | 70.26 |
| 980. | 32.667 | 55.82 | 67.49 | 79.16 |
| 982. | 32.733 | 61.42 | 77.80 | 94.18 |
| 984. | 32.800 | .00 | .00 | .00 |
| 986. | 32.867 | 56.48 | 75.40 | 94.31 |
| 988. | 32.933 | 49.68 | 61.90 | 74.12 |
| 990. | 33.000 | 49.10 | 59.17 | 69.24 |
| 992. | 33.067 | 51.39 | 60.88 | 70.37 |
| 994. | 33.133 | 53.20 | 62.29 | 71.38 |
| 996. | 33.200 | 52.19 | 59.99 | 67.79 |
| 998. | 33.267 | 48.70 | 54.86 | 61.02 |
| 1000. | 33.333 | 44.19 | 49.02 | 53.86 |
| 1002. | 33.400 | 39.96 | 43.89 | 47.82 |
| 1004. | 33.467 | 36.62 | 39.93 | 43.24 |
| 1006. | 33.533 | 34.12 | 36.94 | 39.77 |
| 1008. | 33.600 | 32.19 | 34.65 | 37.11 |
| 1010. | 33.667 | 31.55 | 32.81 | 35.08 |
| 1012. | 33.733 | 28.92 | 31.19 | 33.47 |
| 1014. | 33.800 | 27.28 | 29.63 | 31.98 |
| 1016. | 33.867 | 25.65 | 28.01 | 30.37 |
| 1018. | 33.933 | 24.11 | 26.36 | 28.62 |
| 1020. | 34.000 | 22.76 | 24.90 | 27.03 |
| 1022. | 34.067 | 22.03 | 24.14 | 26.25 |
| 1024. | 34.133 | 22.16 | 24.39 | 26.62 |
| 1026. | 34.200 | 22.75 | 25.16 | 27.58 |

TABLE 1 (CONTINUED)

| FREQUENCY (GHZ) | RECIPROCAL CENTIMETER | LOWER CONFIDENCE LIMIT | DB/KMG/M3 | UPPER CONFIDENCE LIMIT |
|---|---|---|---|---|
| 1028. | 34.267 | 23,15 | 25.68 | 28.22 |
| 1030. | 34.333 | 22,97 | 25.57 | 28.18 |
| 1032. | 34.400 | 22,50 | 25.26 | 28.02 |
| 1034. | 34.467 | 22,52 | 25.55 | 28.57 |
| 1036. | 34.533 | 23,23 | 26.49 | 29.75 |
| 1038. | 34.600 | 24,06 | 27.40 | 30.74 |
| 1040. | 34.667 | 24,45 | 27.78 | 31.10 |
| 1042. | 34.733 | 24,56 | 27.91 | 31.23 |
| 1044. | 34.800 | 25,31 | 28.65 | 32.00 |
| 1046. | 34.867 | 27,07 | 30.53 | 33.99 |
| 1048. | 34.933 | 29,32 | 33.06 | 36.80 |
| 1050. | 35.000 | 31,35 | 35.47 | 39.59 |
| 1052. | 35.067 | 32,99 | 37.55 | 42.10 |
| 1054. | 35.133 | 34,49 | 39.49 | 44.49 |
| 1056. | 35.200 | 36,34 | 41.66 | 46.97 |
| 1058. | 35.267 | 38,91 | 44.29 | 49.67 |
| 1060. | 35.333 | 42,03 | 47.46 | 52.88 |
| 1062. | 35.400 | 45,16 | 50.91 | 56.66 |
| 1064. | 35.467 | 47,93 | 54.28 | 60.64 |
| 1066. | 35.533 | 50,58 | 58.03 | 65.48 |
| 1068. | 35.600 | 54,78 | 65.37 | 76.97 |
| 1070. | 35.667 | - | * | - |
| 1072. | 35.733 | - | * | - |
| 1074. | 35.800 | - | * | - |
| 1076. | 35.867 | - | * | - |
| 1078. | 35.933 | - | * | - |
| 1080. | 36.000 | - | * | - |
| 1082. | 36.067 | - | * | - |
| 1084. | 36.133 | - | * | - |
| 1086. | 36.200 | - | * | - |
| 1088. | 36.267 | - | * | - |
| 1090. | 36.333 | - | * | - |
| 1092. | 36.400 | - | * | - |
| 1094. | 36.467 | - | * | - |
| 1096. | 36.533 | - | * | - |
| 1098. | 36.600 | - | * | - |
| 1100. | 36.667 | - | * | - |
| 1102. | 36.733 | - | * | - |
| 1104. | 36.800 | - | * | - |
| 1106. | 36.867 | - | * | - |
| 1108. | 36.933 | - | * | - |
| 1110. | 37.000 | - | * | - |

* - BEYOND SENSITIVITY OF INSTRUMENT

TABLE I (CONTINUED)

| FREQUENCY (GHZ) | RECIPROCAL CENTIMETER | LOWER CONFIDENCE LIMIT | DB/KMG/M3 | UPPER CONFIDENCE LIMIT |
|---|---|---|---|---|
| 1112. | 37.067 | - | * | - |
| 1114. | 37.133 | - | * | - |
| 1116. | 37.200 | - | * | - |
| 1118. | 37.267 | - | * | - |
| 1120. | 37.333 | - | * | - |
| 1122. | 37.400 | - | * | - |
| 1124. | 37.467 | - | * | - |
| 1126. | 37.533 | 69.62 | 80.00 | 90.38 |
| 1128. | 37.600 | 65.56 | 73.12 | 80.89 |
| 1130. | 37.667 | 65.19 | 72.45 | 79.71 |
| 1132. | 37.733 | 67.55 | 75.15 | 82.75 |
| 1134. | 37.800 | 70.48 | 79.33 | 88.18 |
| 1136. | 37.867 | 74.35 | 87.81 | 101.27 |
| 1138. | 37.933 | - | * | - |
| 1140. | 38.000 | - | * | - |
| 1142. | 38.067 | - | * | - |
| 1144. | 38.133 | - | * | - |
| 1146. | 38.200 | - | * | - |
| 1148. | 38.267 | - | * | - |
| 1150. | 38.333 | 58.26 | 77.15 | 96.03 |
| 1152. | 38.400 | 55.46 | 68.95 | 82.45 |
| 1154. | 38.467 | 56.45 | 71.40 | 86.34 |
| 1156. | 38.533 | - | * | - |
| 1158. | 38.600 | - | * | - |
| 1160. | 38.667 | - | * | - |
| 1162. | 38.733 | - | * | - |
| 1164. | 38.800 | - | * | - |
| 1166. | 38.867 | - | * | - |
| 1168. | 38.933 | - | * | - |
| 1170. | 39.000 | - | * | - |
| 1172. | 39.067 | - | * | - |
| 1174. | 39.133 | - | * | - |
| 1176. | 39.200 | 71.22 | 84.83 | 98.45 |
| 1178. | 39.267 | 77.10 | 91.73 | 106.37 |
| 1180. | 39.333 | - | * | - |
| 1182. | 39.400 | - | * | - |
| 1184. | 39.467 | - | * | - |
| 1186. | 39.533 | - | * | - |
| 1188. | 39.600 | - | * | - |
| 1190. | 39.667 | - | * | - |
| 1192. | 39.733 | - | * | - |
| 1194. | 39.800 | - | * | - |

* - BEYOND SENSITIVITY OF INSTRUMENT

TABLE I (CONTINUED)

| FREQUENCY (GHZ) | RECIPROCAL CENTIMETER | LOWER CONFIDENCE LIMIT | DB/KMG/M3 | UPPER CONFIDENCE LIMIT |
|---|---|---|---|---|
| 1196. | 39.867 | - | * | - |
| 1198. | 39.933 | - | * | - |
| 1200. | 40.000 | - | * | - |
| 1202. | 40.067 | - | * | - |
| 1204. | 40.133 | - | * | - |
| 1206. | 40.200 | - | * | - |
| 1208. | 40.267 | - | * | - |
| 1210. | 40.333 | - | * | - |
| 1212. | 40.400 | - | * | - |
| 1214. | 40.467 | - | * | - |
| 1216. | 40.533 | - | * | - |
| 1218. | 40.600 | - | * | - |
| 1220. | 40.667 | - | * | - |
| 1222. | 40.733 | - | * | - |
| 1224. | 40.800 | - | * | - |
| 1226. | 40.867 | - | * | - |
| 1228. | 40.933 | - | * | - |
| 1230. | 41.000 | - | * | - |
| 1232. | 41.067 | - | * | - |
| 1234. | 41.133 | - | * | - |
| 1236. | 41.200 | - | * | - |
| 1238. | 41.267 | - | * | - |
| 1240. | 41.333 | - | * | - |
| 1242. | 41.400 | - | * | - |
| 1244. | 41.467 | 66,60 | 74.79 | 82.99 |
| 1246. | 41.533 | 61,86 | 69.31 | 76.75 |
| 1248. | 41.600 | 57,76 | 65.01 | 72.23 |
| 1250. | 41.667 | 53,56 | 59.62 | 65.67 |
| 1252. | 41.733 | 49,96 | 54.73 | 59.50 |
| 1254. | 41.800 | 47,30 | 51.35 | 55.40 |
| 1256. | 41.867 | 45,62 | 49.46 | 53.31 |
| 1258. | 41.933 | 44,17 | 48.30 | 52.43 |
| 1260. | 42.000 | 42,63 | 47.14 | 51.66 |
| 1262. | 42.067 | 41,14 | 45.77 | 50.40 |
| 1264. | 42.133 | 39,83 | 44.21 | 48.60 |
| 1266. | 42.200 | 38,97 | 42.96 | 46.95 |
| 1268. | 42.267 | 38,75 | 42.44 | 46.12 |
| 1270. | 42.333 | 38,99 | 42.74 | 46.48 |
| 1272. | 42.400 | 40,02 | 44.16 | 48.30 |
| 1274. | 42.467 | 42,36 | 46.82 | 51.27 |
| 1276. | 42.533 | 45,51 | 50.00 | 54.49 |
| 1278. | 42.600 | 47,42 | 51.96 | 56.50 |

* - BEYOND SENSITIVITY OF INSTRUMENT

TABLE I (CONTINUED)

| FREQUENCY (GHZ) | RECIPROCAL CENTIMETER | LOWER CONFIDENCE LIMIT | DB/KMG/M3 | UPPER CONFIDENCE LIMIT |
|---|---|---|---|---|
| 1280. | 42.667 | 46,41 | 51.13 | 55.85 |
| 1282. | 42.733 | 42,87 | 47.69 | 52.51 |
| 1284. | 42.800 | 38,57 | 43.26 | 47.94 |
| 1286. | 42.867 | 35,02 | 39.44 | 43.87 |
| 1288. | 42.933 | 33,02 | 37.14 | 41.25 |
| 1290. | 43.000 | 32,93 | 36.77 | 40.61 |
| 1292. | 43.067 | 34,40 | 38.09 | 41.78 |
| 1294. | 43.133 | 36,32 | 40.11 | 43.90 |
| 1296. | 43.200 | 37,30 | 41.51 | 45.73 |
| 1298. | 43.267 | 36,54 | 41.13 | 45.73 |
| 1300. | 43.333 | 34,29 | 38.53 | 42.77 |
| 1302. | 43.400 | 31,75 | 35.24 | 38.74 |
| 1304. | 43.467 | 29,93 | 33.00 | 36.07 |
| 1306. | 43.533 | 29,36 | 32.28 | 35.19 |
| 1308. | 43.600 | 30,19 | 33.14 | 36.09 |
| 1310. | 43.667 | 32,22 | 35.52 | 38.83 |
| 1312. | 43.733 | 35,17 | 38.91 | 42.66 |
| 1314. | 43.800 | 38,91 | 43.14 | 47.38 |
| 1316. | 43.867 | 43,36 | 48.60 | 53.82 |
| 1318. | 43.933 | 48,56 | 55.84 | 63.11 |
| 1320. | 44.000 | 53,96 | 64.73 | 75.49 |
| 1322. | 44.067 | 56,28 | 70.11 | 83.94 |
| 1324. | 44.133 | 51,97 | 63.34 | 74.71 |
| 1326. | 44.200 | 45,77 | 53.73 | 61.70 |
| 1328. | 44.267 | 39,68 | 45.74 | 51.60 |
| 1330. | 44.333 | 35,30 | 40.02 | 44.74 |
| 1332. | 44.400 | 32,68 | 36.73 | 40.78 |
| 1334. | 44.467 | 31,14 | 34.85 | 38.57 |
| 1336. | 44.533 | 29,82 | 33.37 | 36.91 |
| 1338. | 44.600 | 28,57 | 31.91 | 35.25 |
| 1340. | 44.667 | 27,51 | 30.62 | 33.73 |
| 1342. | 44.733 | 26,94 | 29.82 | 32.71 |
| 1344. | 44.800 | 26,72 | 29.46 | 32.20 |
| 1346. | 44.867 | 26,16 | 28.88 | 31.60 |
| 1348. | 44.933 | 25,35 | 28.03 | 30.73 |
| 1350. | 45.000 | 25,04 | 27.73 | 30.42 |
| 1352. | 45.067 | 25,77 | 28.54 | 31.31 |
| 1354. | 45.133 | 27,01 | 29.97 | 32.94 |
| 1356. | 45.200 | 27,80 | 30.95 | 34.10 |
| 1358. | 45.267 | 27,83 | 31.03 | 34.24 |
| 1360. | 45.333 | 27,72 | 30.83 | 33.93 |
| 1362. | 45.400 | 28,12 | 31.24 | 34.35 |

TABLE I (CONTINUED)

| FREQUENCY (GHZ) | RECIPROCAL CENTIMETER | LOWER CONFIDENCE LIMIT | DB/KMG/M3 | UPPER CONFIDENCE LIMIT |
|---|---|---|---|---|
| 1364. | 45.467 | 29.10 | 32.35 | 35.60 |
| 1366. | 45.533 | 30.39 | 33.67 | 36.95 |
| 1368. | 45.600 | 31.46 | 34.98 | 38.49 |
| 1370. | 45.667 | 32.55 | 36.60 | 40.65 |
| 1372. | 45.733 | 34.22 | 38.84 | 43.46 |
| 1374. | 45.800 | 35.99 | 41.24 | 46.48 |
| 1376. | 45.867 | 37.34 | 42.87 | 48.39 |
| 1378. | 45.933 | 38.29 | 43.73 | 49.17 |
| 1380. | 46.000 | 39.37 | 44.91 | 50.45 |
| 1382. | 46.067 | 41.35 | 47.32 | 53.31 |
| 1384. | 46.133 | 44.21 | 51.03 | 57.84 |
| 1386. | 46.200 | 47.10 | 54.96 | 62.82 |
| 1388. | 46.267 | 49.36 | 58.35 | 67.34 |
| 1390. | 46.333 | 51.08 | 61.04 | 71.00 |
| 1392. | 46.400 | 53.04 | 63.74 | 74.44 |
| 1394. | 46.467 | 56.96 | 70.07 | 83.16 |
| 1396. | 46.533 | - | * | - |
| 1398. | 46.600 | - | * | - |
| 1400. | 46.667 | - | * | - |
| 1402. | 46.733 | - | * | - |
| 1404. | 46.800 | - | * | - |
| 1406. | 46.867 | 42.39 | 53.25 | 64.12 |
| 1408. | 46.933 | 35.00 | 44.12 | 53.24 |
| 1410. | 47.000 | 38.89 | 61.09 | 83.30 |
| 1412. | 47.067 | - | * | - |
| 1414. | 47.133 | - | * | - |
| 1416. | 47.200 | 55.96 | 79.07 | 102.15 |
| 1418. | 47.267 | 52.54 | 67.15 | 81.77 |
| 1420. | 47.333 | 54.46 | 71.30 | 88.14 |
| 1422. | 47.400 | 57.77 | 80.80 | 103.84 |
| 1424. | 47.467 | 55.31 | 70.54 | 85.77 |
| 1426. | 47.533 | 55.89 | 68.26 | 80.64 |
| 1428. | 47.600 | 57.83 | 69.87 | 81.92 |
| 1430. | 47.667 | 58.76 | 70.67 | 82.63 |
| 1432. | 47.733 | 56.95 | 68.10 | 79.26 |
| 1434. | 47.800 | 54.97 | 66.90 | 78.83 |
| 1436. | 47.867 | 55.75 | 72.41 | 89.09 |
| 1438. | 47.933 | - | * | - |
| 1440. | 48.000 | 52.46 | 64.50 | 76.52 |
| 1442. | 48.067 | 48.06 | 55.18 | 62.30 |
| 1444. | 48.133 | 44.08 | 49.12 | 54.16 |
| 1446. | 48.200 | 40.96 | 45.14 | 49.30 |

* - BEYOND SENSITIVITY OF INSTRUMENT

TABLE 1 (CONTINUED)

| FREQUENCY (GHZ) | RECIPROCAL CENTIMETER | LOWER CONFIDENCE LIMIT | DB/KMG/M3 | UPPER CONFIDENCE LIMIT |
|---|---|---|---|---|
| 1448. | 48.267 | 39.09 | 43.04 | 46.99 |
| 1450. | 48.333 | 38.07 | 42.07 | 46.06 |
| 1452. | 48.400 | 37.15 | 40.99 | 44.84 |
| 1454. | 48.467 | 35.81 | 39.28 | 42.76 |
| 1456. | 48.533 | 34.19 | 37.31 | 40.43 |
| 1458. | 48.600 | 32.80 | 35.74 | 38.69 |
| 1460. | 48.667 | 31.99 | 34.97 | 37.95 |
| 1462. | 48.733 | 31.96 | 35.00 | 38.05 |
| 1464. | 48.800 | 32.36 | 35.50 | 38.64 |
| 1466. | 48.867 | 32.65 | 35.98 | 39.30 |
| 1468. | 48.933 | 32.49 | 35.92 | 39.35 |
| 1470. | 49.000 | 31.63 | 35.25 | 38.87 |
| 1472. | 49.067 | 30.14 | 34.17 | 38.21 |
| 1474. | 49.133 | 28.75 | 32.89 | 37.04 |
| 1476. | 49.200 | 27.94 | 31.78 | 35.62 |
| 1478. | 49.267 | 27.38 | 30.86 | 34.34 |
| 1480. | 49.333 | 26.35 | 29.58 | 32.80 |
| 1482. | 49.400 | 24.64 | 27.73 | 30.83 |
| 1484. | 49.467 | 23.40 | 26.51 | 29.61 |
| 1486. | 49.533 | 24.53 | 27.65 | 30.78 |
| 1488. | 49.600 | 27.88 | 31.03 | 34.18 |
| 1490. | 49.667 | 30.54 | 33.93 | 37.33 |
| 1492. | 49.733 | 30.39 | 34.06 | 37.72 |
| 1494. | 49.800 | 27.96 | 31.51 | 35.05 |
| 1496. | 49.867 | 24.99 | 28.18 | 31.37 |
| 1498. | 49.933 | 22.43 | 25.73 | 29.03 |
| 1500. | 50.000 | 21.71 | 25.08 | 28.46 |
| 1502. | 50.067 | 22.81 | 25.84 | 28.88 |
| 1504. | 50.133 | 24.69 | 27.41 | 30.14 |
| 1506. | 50.200 | 25.60 | 28.81 | 32.02 |
| 1508. | 50.267 | 25.29 | 29.14 | 32.99 |
| 1510. | 50.333 | 24.24 | 27.97 | 31.71 |
| 1512. | 50.400 | 22.72 | 26.12 | 29.53 |
| 1514. | 50.467 | 23.02 | 26.35 | 29.68 |
| 1516. | 50.533 | 24.63 | 28.42 | 32.21 |
| 1518. | 50.600 | 26.15 | 30.63 | 35.10 |
| 1520. | 50.667 | 26.87 | 31.91 | 36.95 |
| 1522. | 50.733 | 27.36 | 31.94 | 36.53 |
| 1524. | 50.800 | 28.57 | 31.86 | 35.15 |
| 1526. | 50.867 | 30.52 | 33.65 | 36.79 |
| 1528. | 50.933 | 32.42 | 36.25 | 40.08 |
| 1530. | 51.000 | 33.43 | 37.82 | 42.22 |

TABLE I (CONTINUED)

| FREQUENCY (GHZ) | RECIPROCAL CENTIMETER | LOWER CONFIDENCE LIMIT | DB/KMG/M3 | UPPER CONFIDENCE LIMIT |
|---|---|---|---|---|
| 1532. | 51.067 | 34,05 | 38.93 | 43.82 |
| 1534. | 51.133 | 35,17 | 40.54 | 45.91 |
| 1536. | 51.200 | 35,58 | 40.61 | 45.64 |
| 1538. | 51.267 | 35,82 | 40.12 | 44.43 |
| 1540. | 51.333 | 37,01 | 41.75 | 46.49 |
| 1542. | 51.400 | 38,90 | 44.80 | 50.69 |
| 1544. | 51.467 | 38,88 | 45.53 | 52.18 |
| 1546. | 51.533 | 35,64 | 42.32 | 48.99 |
| 1548. | 51.600 | 32,35 | 38.68 | 45.01 |
| 1550. | 51.667 | 32,96 | 38.70 | 44.44 |
| 1552. | 51.733 | 37,34 | 42.48 | 47.63 |
| 1554. | 51.800 | 41,41 | 46.36 | 51.31 |
| 1556. | 51.867 | 41,52 | 46.46 | 51.41 |
| 1558. | 51.933 | 37,95 | 42.87 | 47.79 |
| 1560. | 52.000 | 34,09 | 38.80 | 43.52 |
| 1562. | 52.067 | 32,44 | 36.36 | 40.29 |
| 1564. | 52.133 | 33,42 | 37.63 | 41.84 |
| 1566. | 52.200 | 37,19 | 42.35 | 47.50 |
| 1568. | 52.267 | 43,50 | 48.98 | 54.46 |
| 1570. | 52.333 | 51,26 | 57.69 | 64.13 |
| 1572. | 52.400 | - | * | - |
| 1574. | 52.467 | - | * | - |
| 1576. | 52.533 | - | * | - |
| 1578. | 52.600 | - | * | - |
| 1580. | 52.667 | - | * | - |
| 1582. | 52.733 | - | * | - |
| 1584. | 52.800 | - | * | - |
| 1586. | 52.867 | - | * | - |
| 1588. | 52.933 | - | * | - |
| 1590. | 53.000 | - | * | - |
| 1592. | 53.067 | - | * | - |
| 1594. | 53.133 | - | * | - |
| 1596. | 53.200 | - | * | - |
| 1598. | 53.267 | 65,20 | 75.54 | 85.89 |
| 1600. | 53.333 | 57,77 | 68.75 | 79.72 |
| 1602. | 53.400 | - | * | - |
| 1604. | 53.467 | - | * | - |
| 1606. | 53.533 | - | * | - |
| 1608. | 53.600 | - | * | - |
| 1610. | 53.667 | - | * | - |
| 1612. | 53.733 | - | * | - |
| 1614. | 53.800 | - | * | - |

* - BEYOND SENSITIVITY OF INSTRUMENT

TABLE 1 (CONTINUED)

| FREQUENCY (GHZ) | RECIPROCAL CENTIMETER | LOWER CONFIDENCE LIMIT | DB/KMG/M3 | UPPER CONFIDENCE LIMIT |
|---|---|---|---|---|
| 1616. | 53.867 | - | * | - |
| 1618. | 53.933 | - | * | - |
| 1620. | 54.000 | - | * | - |
| 1622. | 54.067 | - | * | - |
| 1624. | 54.133 | - | * | - |
| 1626. | 54.200 | - | * | - |
| 1628. | 54.267 | - | * | - |
| 1630. | 54.333 | - | * | - |
| 1632. | 54.400 | - | * | - |
| 1634. | 54.467 | - | * | - |
| 1636. | 54.533 | - | * | - |
| 1638. | 54.600 | - | * | - |
| 1640. | 54.667 | - | * | - |
| 1642. | 54.733 | - | * | - |
| 1644. | 54.800 | - | * | - |
| 1646. | 54.867 | - | * | - |
| 1648. | 54.933 | - | * | - |
| 1650. | 55.000 | - | * | - |

* - BEYOND SENSITIVITY OF INSTRUMENT

Table II

DATA USED IN PLOTTING SPECTRUM

SHOWN IN FIGURE 8

| Frequency (GHz) | Frequency ($cm^{-1}$) | Atten. Avg. $dB/km/g/m^3$ | Frequency (GHz) | Frequency ($cm^{-1}$) | Atten. Avg. $dB/km/g/m^3$ |
|---|---|---|---|---|---|
| 1080 | 36.000 | 91.544 | 1149 | 38.300 | 558.209 |
| 1083 | 36.100 | 209.636 | 1152 | 38.400 | 556.018 |
| 1086 | 36.200 | 509.138 | 1155 | 38.500 | 692.984 |
| 1089 | 36.300 | 732.048 | 1158 | 38.600 | 739.366 |
| 1092 | 36.400 | 803.633 | 1161 | 38.700 | 710.150 |
| 1095 | 36.500 | 701.660 | 1164 | 38.800 | 573.260 |
| 1098 | 36.600 | 722.570 | 1167 | 38.900 | 440.349 |
| 1101 | 36.700 | 746.576 | 1170 | 39.000 | 389.327 |
| 1104 | 36.800 | 848.549 | 1173 | 39.100 | 246.090 |
| 1107 | 36.900 | 834.009 | 1176 | 39.200 | 198.890 |
| 1110 | 37.000 | 852.488 | 1179 | 39.300 | 136.812 |
| 1113 | 37.100 | 852.488 | 1182 | 39.400 | 117.927 |
| 1116 | 37.200 | 883.122 | 1185 | 39.500 | 111.638 |
| 1119 | 37.300 | 772.762 | 1188 | 39.600 | 102.068 |
| 1122 | 37.400 | 567.643 | 1191 | 39.700 | 107.172 |
| 1125 | 37.500 | 464.590 | 1194 | 39.800 | 135.152 |
| 1128 | 37.600 | 498.441 | 1197 | 39.900 | 182.981 |
| 1131 | 37.700 | 479.492 | 1200 | 40.000 | 290.414 |
| 1134 | 37.800 | 384.142 | 1203 | 40.100 | 400.077 |
| 1137 | 37.900 | 256.061 | 1206 | 40.200 | 401.621 |
| 1140 | 38.000 | 318.822 | 1209 | 40.300 | 305.400 |
| 1143 | 38.100 | 418.144 | 1212 | 40.400 | 172.542 |
| 1146 | 38.200 | 554.283 | 1215 | 40.500 | 144.604 |

Table II (Continued)

| Frequency (GHz) | Frequency ($cm^{-1}$) | Atten. Avg. $dB/km/g/m^3$ | Frequency (GHz) | Frequency ($cm^{-1}$) | Atten. Avg. $dB/km/g/m^3$ |
|---|---|---|---|---|---|
| 1218 | 40.600 | 161.903 | 1308 | 43.600 | 27.376 |
| 1221 | 40.700 | 398.449 | 1311 | 43.700 | 20.477 |
| 1224 | 40.800 | 537.504 | 1314 | 43.800 | 27.348 |
| 1227 | 40.900 | 619.499 | 1317 | 43.900 | 63.399 |
| 1230 | 41.000 | 473.568 | 1320 | 44.000 | 105.316 |
| 1233 | 41.100 | 298.336 | 1323 | 44.100 | 102.588 |
| 1236 | 41.200 | 166.829 | 1326 | 44.200 | 64.229 |
| 1239 | 41.300 | 59.224 | 1329 | 44.300 | 23.391 |
| 1242 | 41.400 | 60.923 | 1332 | 44.400 | 18.859 |
| 1245 | 41.500 | 64.179 | 1335 | 44.500 | 27.449 |
| 1248 | 41.600 | 60.918 | 1338 | 44.600 | 27.559 |
| 1251 | 41.700 | 57.681 | 1341 | 44.700 | 19.940 |
| 1254 | 41.800 | 48.326 | 1344 | 44.800 | 13.294 |
| 1257 | 41.900 | 31.940 | 1347 | 44.900 | 10.817 |
| 1260 | 42.000 | 25.644 | 1350 | 45.000 | 12.193 |
| 1263 | 42.100 | 17.647 | 1353 | 45.100 | 13.230 |
| 1266 | 42.200 | 19.132 | 1356 | 45.200 | 13.272 |
| 1269 | 42.300 | 23.282 | 1359 | 45.300 | 19.546 |
| 1272 | 42.400 | 38.789 | 1362 | 45.400 | 20.068 |
| 1275 | 42.500 | 53.959 | 1365 | 45.500 | 21.853 |
| 1278 | 42.600 | 56.758 | 1368 | 45.600 | 19.347 |
| 1281 | 42.700 | 41.112 | 1371 | 45.700 | 27.256 |
| 1284 | 42.800 | 24.199 | 1374 | 45.800 | 37.844 |
| 1287 | 42.900 | 21.238 | 1377 | 45.900 | 41.001 |
| 1290 | 43.000 | 32.788 | 1380 | 46.000 | 40.228 |
| 1293 | 43.100 | 45.189 | 1383 | 46.100 | 38.648 |
| 1296 | 43.200 | 42.190 | 1386 | 46.200 | 45.554 |
| 1299 | 43.300 | 32.000 | 1389 | 46.300 | 57.022 |
| 1302 | 43.400 | 27.858 | 1392 | 46.400 | 81.368 |
| 1305 | 43.500 | 29.001 | 1395 | 46.500 | 129.387 |

Table II (Continued)

| Frequency (GHz) | Frequency ($cm^{-1}$) | Atten. Avg. $dB/km/g/m^3$ | Frequency (GHz) | Frequency ($cm^{-1}$) | Atten. Avg. $dB/km/g/m^3$ |
|---|---|---|---|---|---|
| 1398 | 46.600 | 287.824 | 1488 | 49.600 | 23.586 |
| 1401 | 46.700 | 582.081 | 1491 | 49.700 | 23.346 |
| 1404 | 46.800 | 848.826 | 1494 | 49.800 | 20.722 |
| 1407 | 46.900 | 910.031 | 1497 | 49.900 | 21.448 |
| 1410 | 47.000 | 758.537 | 1500 | 50.000 | 21.049 |
| 1413 | 47.100 | 576.577 | 1503 | 50.100 | 17.943 |
| 1416 | 47.200 | 383.493 | 1524 | 50.800 | 32.119 |
| 1419 | 47.300 | 242.422 | 1527 | 50.900 | 32.866 |
| 1422 | 47.400 | 122.374 | 1530 | 51.000 | 24.913 |
| 1425 | 47.500 | 100.954 | 1533 | 51.100 | 22.123 |
| 1428 | 47.600 | 86.394 | 1536 | 51.200 | 38.543 |
| 1431 | 47.700 | 74.297 | 1539 | 51.300 | 63.208 |
| 1434 | 47.800 | 61.704 | 1542 | 51.400 | 69.596 |
| 1437 | 47.900 | 56.389 | 1545 | 51.500 | 62.439 |
| 1440 | 48.000 | 55.022 | 1548 | 51.600 | 42.146 |
| 1443 | 48.100 | 51.792 | 1551 | 51.700 | 33.467 |
| 1446 | 48.200 | 38.712 | 1554 | 51.800 | 31.910 |
| 1449 | 48.300 | 28.832 | 1557 | 51.900 | 33.120 |
| 1452 | 48.400 | 24.087 | 1560 | 52.000 | 33.442 |
| 1455 | 48.500 | 28.276 | 1563 | 52.100 | 31.264 |
| 1458 | 48.600 | 32.457 | 1566 | 52.200 | 31.854 |
| 1461 | 48.700 | 36.148 | 1569 | 52.300 | 34.912 |
| 1464 | 48.800 | 33.302 | 1572 | 52.400 | 38.583 |
| 1467 | 48.900 | 31.863 | 1575 | 52.500 | 45.993 |
| 1470 | 49.000 | 31.127 | 1578 | 52.600 | 58.404 |
| 1473 | 49.100 | 31.019 | 1581 | 52.700 | 79.688 |
| 1476 | 49.200 | 26.766 | 1584 | 52.800 | 104.804 |
| 1479 | 49.300 | 19.804 | 1587 | 52.900 | 131.589 |
| 1482 | 49.400 | 18.848 | 1590 | 53.000 | 261.784 |
| 1485 | 49.500 | 20.131 | 1593 | 53.100 | 503.667 |

Table II (Continued)

| Frequency (GHz) | Frequency ($cm^{-1}$) | Atten. Avg. $dB/km/g/m^3$ | Frequency (GHz) | Frequency ($cm^{-1}$) | Atten. Avg. $dB/km/g/m^3$ |
|---|---|---|---|---|---|
| 1596 | 53.200 | 784.853 | 1692 | 56.400 | 478.900 |
| 1599 | 53.300 | 913.782 | 1695 | 56.500 | 494.463 |
| 1602 | 53.400 | 815.191 | 1698 | 56.600 | 494.230 |
| 1605 | 53.500 | 630.982 | 1701 | 56.700 | 585.841 |
| 1608 | 53.600 | 390.717 | 1704 | 56.800 | 623.369 |
| 1611 | 53.700 | 237.680 | 1707 | 56.900 | 568.484 |
| 1614 | 53.800 | 124.963 | 1710 | 57.000 | 470.899 |
| 1617 | 53.900 | 103.727 | 1713 | 57.100 | 351.563 |
| 1620 | 54.000 | 100.707 | 1716 | 57.200 | 341.227 |
| 1623 | 54.100 | 109.140 | 1719 | 57.300 | 408.468 |
| 1626 | 54.200 | 129.663 | 1722 | 57.400 | 398.406 |
| 1629 | 54.300 | 156.978 | 1725 | 57.500 | 387.383 |
| 1632 | 54.400 | 163.827 | 1728 | 57.600 | 286.177 |
| 1635 | 54.500 | 171.184 | 1731 | 57.700 | 231.230 |
| 1638 | 54.600 | 197.990 | 1734 | 57.800 | 168.280 |
| 1641 | 54.700 | 249.258 | 1737 | 57.900 | 134.479 |
| 1644 | 54.800 | 468.036 | 1740 | 58.000 | 130.258 |
| 1647 | 54.900 | 641.954 | 1743 | 58.100 | 123.171 |
| 1650 | 55.000 | 872.330 | 1746 | 58.200 | 128.234 |
| 1653 | 55.100 | 926.510 | 1749 | 58.300 | 150.672 |
| 1656 | 55.200 | 1000.000 | 1752 | 58.400 | 182.960 |
| 1659 | 55.300 | 1000.000 | 1755 | 58.500 | 245.627 |
| 1662 | 55.400 | 1000.000 | 1758 | 58.600 | 329.512 |
| 1665 | 55.500 | 1000.000 | 1761 | 58.700 | 421.546 |
| 1668 | 55.600 | 1000.000 | 1764 | 58.800 | 452.163 |
| 1671 | 55.700 | 1000.000 | 1767 | 58.900 | 344.788 |
| 1674 | 55.800 | 881.230 | 1770 | 59.000 | 213.419 |
| 1677 | 55.900 | 806.802 | 1773 | 59.100 | 101.866 |
| 1680 | 56.000 | 727.586 | 1776 | 59.200 | 93.826 |
| 1683 | 56.100 | 718.473 | 1779 | 59.300 | 106.018 |
| 1686 | 56.200 | 635.139 | 1782 | 59.400 | 144.813 |
| 1689 | 56.300 | 567.043 | 1785 | 59.500 | 318.149 |

Table II (Continued)

| Frequency (GHz) | Frequency ($cm^{-1}$) | Atten. Avg. $dB/km/g/m^3$ | Frequency (GHz) | Frequency ($cm^{-1}$) | Atten. Avg. $dB/km/g/m^3$ |
|---|---|---|---|---|---|
| 1788 | 59.600 | 555.064 | 1878 | 62.600 | 175.794 |
| 1791 | 59.700 | 652.569 | 1881 | 62.700 | 147.078 |
| 1794 | 59.800 | 602.921 | 1884 | 62.800 | 118.679 |
| 1797 | 59.900 | 433.852 | 1887 | 62.900 | 98.063 |
| 1800 | 60.000 | 335.958 | 1890 | 63.000 | 80.611 |
| 1803 | 60.100 | 215.354 | 1893 | 63.100 | 67.348 |
| 1806 | 60.200 | 126.569 | 1896 | 63.200 | 67.901 |
| 1809 | 60.300 | 85.072 | 1899 | 63.300 | 78.790 |
| 1812 | 60.400 | 75.926 | 1902 | 63.400 | 95.597 |
| 1815 | 60.500 | 71.080 | 1905 | 63.500 | 150.082 |
| 1818 | 60.600 | 57.859 | 1908 | 63.600 | 397.674 |
| 1821 | 60.700 | 47.428 | 1911 | 63.700 | 692.120 |
| 1824 | 60.800 | 46.739 | 1914 | 63.800 | 946.318 |
| 1827 | 60.900 | 50.702 | 1917 | 63.900 | 936.440 |
| 1830 | 61.000 | 55.294 | 1920 | 64.000 | 763.514 |
| 1833 | 61.100 | 56.751 | 1923 | 64.100 | 569.850 |
| 1836 | 61.200 | 59.321 | 1926 | 64.200 | 342.423 |
| 1839 | 61.300 | 63.972 | 1929 | 64.300 | 216.581 |
| 1842 | 61.400 | 70.487 | 1932 | 64.400 | 106.387 |
| 1845 | 61.500 | 83.916 | 1935 | 64.500 | 91.929 |
| 1848 | 61.600 | 100.680 | 1938 | 64.600 | 78.848 |
| 1851 | 61.700 | 124.301 | 1941 | 64.700 | 70.459 |
| 1854 | 61.800 | 163.051 | 1944 | 64.800 | 61.060 |
| 1857 | 61.900 | 304.498 | 1947 | 64.900 | 53.070 |
| 1860 | 62.000 | 407.287 | 1950 | 65.000 | 47.262 |
| 1863 | 62.100 | 537.530 | 1953 | 65.100 | 40.547 |
| 1866 | 62.200 | 464.721 | 1956 | 65.200 | 36.250 |
| 1869 | 62.300 | 401.556 | 1959 | 65.300 | 30.089 |
| 1872 | 62.400 | 265.890 | 1962 | 65.400 | 27.722 |
| 1875 | 62.500 | 220.477 | 1965 | 65.500 | 29.980 |

Table II (Continued)

| Frequency (GHz) | Frequency ($cm^{-1}$) | Atten. Avg. $dB/km/g/m^3$ | Frequency (GHz) | Frequency ($cm^{-1}$) | Atten. Avg. $dB/km/g/m^3$ |
|---|---|---|---|---|---|
| 1968 | 65.600 | 34.534 | 2058 | 68.600 | 91.346 |
| 1971 | 65.700 | 37.293 | 2061 | 68.700 | 123.208 |
| 1974 | 65.800 | 40.166 | 2064 | 68.800 | 281.231 |
| 1977 | 65.900 | 38.636 | 2067 | 68.900 | 576.742 |
| 1980 | 66.000 | 37.643 | 2070 | 69.000 | 720.470 |
| 1983 | 66.100 | 35.090 | 2073 | 69.100 | 678.694 |
| 1986 | 66.200 | 31.754 | 2076 | 69.200 | 482.580 |
| 1989 | 66.300 | 31.058 | 2079 | 69.300 | 338.154 |
| 1992 | 66.400 | 27.961 | 2082 | 69.400 | 227.628 |
| 1995 | 66.500 | 25.653 | 2085 | 69.500 | 112.599 |
| 1998 | 66.600 | 23.159 | 2088 | 69.600 | 70.590 |
| 2001 | 66.700 | 21.518 | 2091 | 69.700 | 52.168 |
| 2004 | 66.800 | 31.346 | 2094 | 69.800 | 45.161 |
| 2007 | 66.900 | 58.453 | 2097 | 69.900 | 43.666 |
| 2010 | 67.000 | 113.048 | 2100 | 70.000 | 47.016 |
| 2013 | 67.100 | 156.041 | 2103 | 70.100 | 49.126 |
| 2016 | 67.200 | 148.828 | 2106 | 70.200 | 52.404 |
| 2019 | 67.300 | 108.014 | 2109 | 70.300 | 55.120 |
| 2022 | 67.400 | 74.959 | 2112 | 70.400 | 59.202 |
| 2025 | 67.500 | 86.122 | 2115 | 70.500 | 59.216 |
| 2028 | 67.600 | 209.200 | 2118 | 70.600 | 53.591 |
| 2031 | 67.700 | 352.448 | 2121 | 70.700 | 46.894 |
| 2034 | 67.800 | 563.260 | 2124 | 70.800 | 51.546 |
| 2037 | 67.900 | 594.050 | 2127 | 70.900 | 57.111 |
| 2040 | 68.000 | 514.116 | 2130 | 71.000 | 67.788 |
| 2043 | 68.100 | 342.433 | 2133 | 71.100 | 86.453 |
| 2046 | 68.200 | 209.086 | 2136 | 71.200 | 108.504 |
| 2049 | 68.300 | 156.661 | 2139 | 71.300 | 149.319 |
| 2052 | 68.400 | 103.488 | 2142 | 71.400 | 262.471 |
| 2055 | 68.500 | 90.676 | 2145 | 71.500 | 393.814 |

Table II (Continued)

| Frequency (GHz) | Frequency ($cm^{-1}$) | Atten. Avg. dB/km/g/$m^3$ | Frequency (GHz) | Frequency ($cm^{-1}$) | Atten. Avg. dB/km/g/$m^3$ |
|---|---|---|---|---|---|
| 2148 | 71.600 | 540.286 | 2241 | 74.700 | 667.322 |
| 2151 | 71.700 | 638.494 | 2244 | 74.800 | 598.121 |
| 2154 | 71.800 | 796.602 | 2247 | 74.900 | 513.396 |
| 2157 | 71.900 | 917.294 | 2250 | 75.000 | 541.201 |
| 2160 | 72.000 | 952.752 | 2253 | 75.100 | 762.884 |
| 2163 | 72.100 | 834.541 | 2256 | 75.200 | 817.099 |
| 2166 | 72.200 | 648.297 | 2259 | 75.300 | 913.572 |
| 2169 | 72.300 | 533.294 | 2262 | 75.400 | 913.572 |
| 2172 | 72.400 | 401.678 | 2265 | 75.500 | 1000.000 |
| 2175 | 72.500 | 355.366 | 2268 | 75.600 | 841.432 |
| 2178 | 72.600 | 369.500 | 2271 | 75.700 | 658.602 |
| 2181 | 72.700 | 477.824 | 2274 | 75.800 | 461.358 |
| 2184 | 72.800 | 640.322 | 2277 | 75.900 | 319.827 |
| 2187 | 72.900 | 708.982 | 2280 | 76.000 | 203.098 |
| 2190 | 73.000 | 850.486 | 2283 | 76.100 | 100.142 |
| 2193 | 73.100 | 920.544 | 2286 | 76.200 | 94.501 |
| 2196 | 73.200 | 937.949 | 2289 | 76.300 | 92.910 |
| 2199 | 73.300 | 795.333 | 2292 | 76.400 | 91.340 |
| 2202 | 73.400 | 613.561 | 2295 | 76.500 | 95.069 |
| 2205 | 73.500 | 547.393 | 2298 | 76.600 | 90.169 |
| 2208 | 73.600 | 669.929 | 2301 | 76.700 | 83.852 |
| 2211 | 73.700 | 851.701 | 2304 | 76.800 | 78.692 |
| 2214 | 73.800 | 979.920 | 2307 | 76.900 | 80.742 |
| 2217 | 73.900 | 1000.000 | 2310 | 77.000 | 105.497 |
| 2220 | 74.000 | 1000.000 | 2313 | 77.100 | 148.240 |
| 2223 | 74.100 | 918.238 | 2316 | 77.200 | 168.739 |
| 2226 | 74.200 | 759.012 | 2319 | 77.300 | 153.246 |
| 2229 | 74.300 | 594.127 | 2322 | 77.400 | 114.489 |
| 2232 | 74.400 | 509.146 | 2325 | 77.500 | 105.921 |
| 2235 | 74.500 | 515.889 | 2328 | 77.600 | 126.910 |
| 2238 | 74.600 | 624.858 | 2331 | 77.700 | 191.872 |

Table II (Continued)

| Frequency (GHz) | Frequency ($cm^{-1}$) | Atten. Avg, $dB/km/g/m^3$ | Frequency (GHz) | Frequency ($cm^{-1}$) | Atten. Avg, $dB/km/g/m^3$ |
|---|---|---|---|---|---|
| 2334 | 77.800 | 372.941 | 2433 | 81.100 | 148.487 |
| 2337 | 77.900 | 539.778 | 2436 | 81.200 | 133.997 |
| 2340 | 78.000 | 778.000 | 2439 | 81.300 | 185.390 |
| 2343 | 78.100 | 889.000 | 2442 | 81.400 | 319.031 |
| 2346 | 78.200 | 848.997 | 2445 | 81.500 | 442.472 |
| 2349 | 78.300 | 686.174 | 2448 | 81.600 | 520.112 |
| 2352 | 78.400 | 464.950 | 2451 | 81.700 | 475.254 |
| 2355 | 78.500 | 543.264 | 2454 | 81.800 | 554.822 |
| 2358 | 78.600 | 706.087 | 2457 | 81.900 | 583.257 |
| 2361 | 78.700 | 858.540 | 2460 | 82.000 | 695.346 |
| 2364 | 78.800 | 931.229 | 2463 | 82.100 | 690.459 |
| 2367 | 78.900 | 775.430 | 2466 | 82.200 | 660.983 |
| 2370 | 79.000 | 683.928 | 2469 | 82.300 | 552.964 |
| 2373 | 79.100 | 541.764 | 2472 | 82.400 | 360.077 |
| 2376 | 79.200 | 681.453 | 2475 | 82.500 | 227.882 |
| 2379 | 79.300 | 841.727 | 2478 | 82.600 | 121.624 |
| 2382 | 79.400 | 983.890 | 2481 | 82.700 | 82.967 |
| 2385 | 79.500 | 1000.000 | 2484 | 82.800 | 59.067 |
| 2388 | 79.600 | 1000.000 | 2487 | 82.900 | 48.614 |
| 2391 | 79.700 | 915.210 | 2490 | 83.000 | 48.932 |
| 2394 | 79.800 | 758.507 | 2493 | 83.100 | 39.260 |
| 2397 | 79.900 | 591.904 | 2496 | 83.200 | 29.880 |
| 2400 | 80.000 | 503.442 | 2499 | 83.300 | 25.793 |
| 2403 | 80.100 | 471.947 | 2502 | 83.400 | 34.271 |
| 2406 | 80.200 | 358.118 | 2505 | 83.500 | 39.152 |
| 2409 | 80.300 | 246.921 | 2508 | 83.600 | 36.904 |
| 2412 | 80.400 | 153.512 | 2511 | 83.700 | 32.340 |
| 2415 | 80.500 | 165.729 | 2514 | 83.800 | 28.177 |
| 2418 | 80.600 | 185.303 | 2517 | 83.900 | 28.342 |
| 2421 | 80.700 | 220.734 | 2520 | 84.000 | 31.017 |
| 2424 | 80.800 | 321.171 | 2523 | 84.100 | 37.866 |
| 2427 | 80.900 | 315.870 | 2526 | 84.200 | 47.244 |
| 2430 | 81.000 | 272.497 | 2529 | 84.300 | 54.613 |

Table II (Continued)

| Frequency (GHz) | Frequency ($cm^{-1}$) | Atten. Avg. $dB/km/g/m^3$ | Frequency (GHz) | Frequency ($cm^{-1}$) | Atten. Avg. $dB/km/g/m^3$ |
|---|---|---|---|---|---|
| 2532 | 84.400 | 51.134 | 2628 | 87.600 | 778.000 |
| 2535 | 84.500 | 39.024 | 2631 | 87.700 | 889.000 |
| 2538 | 84.600 | 24.277 | 2634 | 87.800 | 1000.000 |
| 2541 | 84.700 | 19.500 | 2637 | 87.900 | 1000.000 |
| 2544 | 84.800 | 23.777 | 2640 | 88.000 | 1000.000 |
| 2547 | 84.900 | 29.482 | 2643 | 88.100 | 1000.000 |
| 2550 | 85.000 | 45.983 | 2646 | 88.200 | 1000.000 |
| 2553 | 85.100 | 67.139 | 2649 | 88.300 | 1000.000 |
| 2556 | 85.200 | 86.016 | 2652 | 88.400 | 1000.000 |
| 2559 | 85.300 | 116.803 | 2655 | 88.500 | 962.777 |
| 2562 | 85.400 | 158.462 | 2658 | 88.600 | 962.777 |
| 2565 | 85.500 | 195.538 | 2661 | 88.700 | 919.620 |
| 2568 | 85.600 | 195.673 | 2664 | 88.800 | 874.572 |
| 2571 | 85.700 | 155.743 | 2667 | 88.900 | 874.572 |
| 2574 | 85.800 | 115.093 | 2670 | 89.000 | 917.729 |
| 2577 | 85.900 | 78.704 | 2673 | 89.100 | 1000.000 |
| 2580 | 86.000 | 73.851 | 2676 | 89.200 | 889.000 |
| 2583 | 86.100 | 84.103 | 2679 | 89.300 | 889.000 |
| 2586 | 86.200 | 109.988 | 2682 | 89.400 | 889.000 |
| 2589 | 86.300 | 138.098 | 2685 | 89.500 | 931.893 |
| 2592 | 86.400 | 151.344 | 2688 | 89.600 | 760.329 |
| 2595 | 86.500 | 160.691 | 2691 | 89.700 | 567.712 |
| 2598 | 86.600 | 164.441 | 2694 | 89.800 | 436.120 |
| 2601 | 86.700 | 189.202 | 2697 | 89.900 | 303.992 |
| 2604 | 86.800 | 304.733 | 2700 | 90.000 | 198.551 |
| 2607 | 86.900 | 414.733 | 2703 | 90.100 | 109.619 |
| 2610 | 87.000 | 590.660 | 2706 | 90.200 | 121.009 |
| 2613 | 87.100 | 754.576 | 2709 | 90.300 | 120.286 |
| 2616 | 87.200 | 815.813 | 2712 | 90.400 | 95.696 |
| 2619 | 87.300 | 898.734 | 2715 | 90.500 | 78.188 |
| 2622 | 87.400 | 787.734 | 2718 | 90.600 | 68.490 |
| 2625 | 87.500 | 778.000 | 2721 | 90.700 | 77.354 |

Table II (Continued)

| Frequency (GHz) | Frequency ($cm^{-1}$) | Atten. Avg. $dB/km/g/m^3$ | Frequency (GHz) | Frequency ($cm^{-1}$) | Atten. Avg. $dB/km/g/m^3$ |
|---|---|---|---|---|---|
| 2724 | 90.800 | 93.162 | 2817 | 93.900 | 215.326 |
| 2727 | 90.900 | 109.242 | 2820 | 94.000 | 209.656 |
| 2730 | 91.000 | 132.236 | 2823 | 94.100 | 99.091 |
| 2733 | 91.100 | 164.432 | 2826 | 94.200 | 98.067 |
| 2736 | 91.200 | 280.966 | 2829 | 94.300 | 120.929 |
| 2739 | 91.300 | 472.196 | 2832 | 94.400 | 130.931 |
| 2742 | 91.400 | 523.840 | 2835 | 94.500 | 142.329 |
| 2745 | 91.500 | 514.128 | 2838 | 94.600 | 143.872 |
| 2748 | 91.600 | 480.896 | 2841 | 94.700 | 137.932 |
| 2751 | 91.700 | 600.328 | 2844 | 94.800 | 130.927 |
| 2754 | 91.800 | 785.906 | 2847 | 94.900 | 123.257 |
| 2757 | 91.900 | 829.098 | 2850 | 95.000 | 142.261 |
| 2760 | 92.000 | 808.827 | 2853 | 95.100 | 170.731 |
| 2763 | 92.100 | 697.827 | 2856 | 95.200 | 282.244 |
| 2766 | 92.200 | 667.000 | 2859 | 95.300 | 411.002 |
| 2769 | 92.300 | 778.000 | 2862 | 95.400 | 560.071 |
| 2772 | 92.400 | 778.000 | 2865 | 95.500 | 627.540 |
| 2775 | 92.500 | 889.000 | 2868 | 95.600 | 778.000 |
| 2778 | 92.600 | 889.000 | 2871 | 95.700 | 778.000 |
| 2781 | 92.700 | 1000.000 | 2874 | 95.800 | 889.000 |
| 2784 | 92.800 | 1000.000 | 2877 | 95.900 | 889.000 |
| 2787 | 92.900 | 842.994 | 2880 | 96.000 | 920.241 |
| 2790 | 93.000 | 674.338 | 2883 | 96.100 | 841.466 |
| 2793 | 93.100 | 510.459 | 2886 | 96.200 | 707.604 |
| 2796 | 93.200 | 489.764 | 2889 | 96.300 | 617.220 |
| 2799 | 93.300 | 464.662 | 2892 | 96.400 | 452.849 |
| 2802 | 93.400 | 435.937 | 2895 | 96.500 | 434.259 |
| 2805 | 93.500 | 427.168 | 2898 | 96.600 | 431.517 |
| 2808 | 93.600 | 419.939 | 2901 | 96.700 | 374.642 |
| 2811 | 93.700 | 311.496 | 2904 | 96.800 | 334.870 |
| 2814 | 93.800 | 306.244 | 2907 | 96.900 | 231.137 |

Table II (Continued)

| Frequency (GHz) | Frequency ($cm^{-1}$) | Atten. Avg. $dB/km/g/m^3$ |
|---|---|---|
| 2910 | 97.000 | 265.680 |
| 2913 | 97.100 | 226.240 |
| 2916 | 97.200 | 217.948 |
| 2919 | 97.300 | 213.939 |
| 2922 | 97.400 | 168.044 |
| 2925 | 97.500 | 256.903 |
| 2928 | 97.600 | 398.508 |
| 2931 | 97.700 | 464.877 |
| 2934 | 97.800 | 518.270 |
| 2937 | 97.900 | 452.860 |
| 2940 | 98.000 | 563.161 |
| 2943 | 98.100 | 613.278 |
| 2946 | 98.200 | 736.957 |
| 2949 | 98.300 | 837.844 |
| 2952 | 98.400 | 930.387 |
| 2955 | 98.500 | 1000.000 |
| 2958 | 98.600 | 1000.000 |
| 2961 | 98.700 | 925.317 |
| 2964 | 98.800 | 816.516 |
| 2967 | 98.900 | 705.516 |
| 2970 | 99.000 | 780.199 |
| 2973 | 99.100 | 820.093 |
| 2976 | 99.200 | 840.120 |
| 2979 | 99.300 | 737.968 |
| 2982 | 99.400 | 806.874 |
| 2985 | 99.500 | 897.848 |
| 2988 | 99.600 | 1000.000 |
| 2991 | 99.700 | 816.237 |
| 2994 | 99.800 | 816.237 |
| 2997 | 99.900 | 816.237 |

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13. ABSTRACT

Measurements on the absorption due to rotational transitions of atmospheric water vapor in the 10 $cm^{-1}$ - 100 $cm^{-1}$ frequency region are reported. Comparison of the measured absorption line center frequencies is made with the theoretical calculations of other investigators. Measured absorption in the atmospheric "windows" is also compared with theoretical predictions. Good agreement is obtained between theory and measurements. A summary of instrumentation used and techniques for processing the data is given. The instrumentation centers about a 30 cm aperture Michelson interference spectrometer and an auxiliary multiple reflection chamber in which a test atmosphere can be monitored and controlled. A discussion of humidity measurement techniques is also presented.

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UNCLASSIFIED

Security Classification

| 14. KEY WORDS | LINK A | | LINK B | | LINK C | |
|---|---|---|---|---|---|---|
| | ROLE | WT | ROLE | WT | ROLE | WT |
| Atmospheric absorption | | | | | | |
| Interference spectroscopy | | | | | | |
| Fourier spectroscopy | | | | | | |
| Atmospheric water vapor attenuation | | | | | | |
| Humidity measurement techniques | | | | | | |

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